ANNUAL RESEARCH REPORT

1993

U.S. WATER CONSERVATION LABORATORY
U.S. Department of Agriculture
Agricultural Research Service
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INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to inform upper level management within the Agricultural Research Service, other ARS research locations involved in natural resources research, and our many collaborators and cooperators about progress on our research projects in 1993 and plans for 1994 and beyond. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, the problem, objectives, approach, brief results--what it all means, future plans, and cooperators. We want to make sure that the product of the research and its contribution to water conservation are clear to all.

In addition to allowing the research staff to tell our research story, this Research Report, together with the Annual Program Review and Planning Meeting held each year in early January, provide an opportunity for us to assess where we are in our programs; to look at the long-range (three-to-five-year) goals and expected outcomes (both long-term and intermediate), one-year goals, and strategies to get there. This year, in response to a Pacific West Area initiative, a first draft of a Long-Range Plan for the USWCL was developed. By planning our research in these ways, goals, outcomes, and strategies are clarified, and appropriate resources can be identified. If you are interested, we would be pleased to share the Long-Range Plan for the USWCL with you.

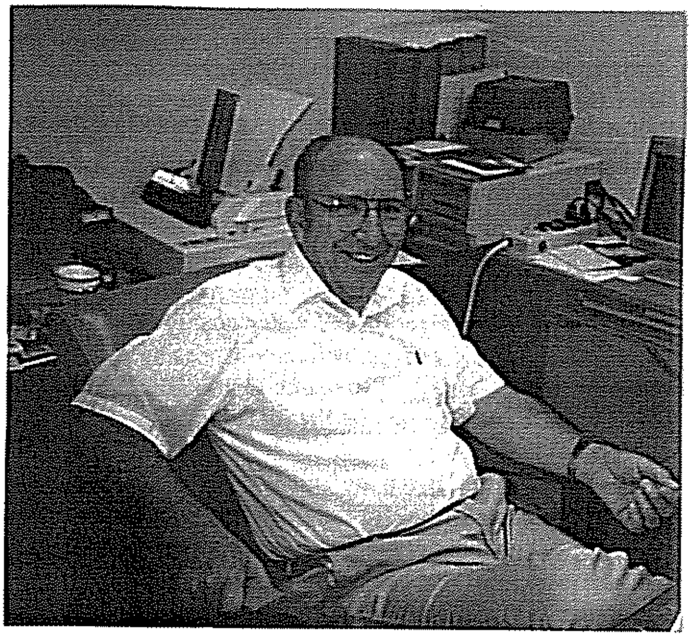
The programs at the USWCL continue to make excellent progress. In all instances, were they available, more ARS resources could be directed productively toward identified, high-priority research being called for by our many and diverse clients. In the absence of additional ARS resources, we strive to leverage our available base funding into well-targeted, broader-based programs by attracting outside resources. We are committed to working collaboratively with other agencies and industry in bringing Post Doctorates, visiting scientists and engineers, graduate students, and persons on sabbaticals to the USWCL to maintain or expand our research programs. The outstanding research expertise of the Laboratory staff has been instrumental in developing and maintaining collaborative programs with research staff from other organizations, national and international, helping to form the critical mass for studying identified research needs. Certainly, outside funding is instrumental in our continued work in major program areas, but the "in-kind" human resources provided by many of our cooperators and collaborators are highly significant, and our programs are enhanced by each individual's stimulating effects on our research efforts (please refer to the list of Cooperators shown at the end of each report).

During 1993, a number of organizations contributed, and/or have indicated they will contribute in the future, significant financial resources in support of the research program at the USWCL. The *Irrigation Group* is receiving outside support through OICD for a three-year collaborative study, which began in 1992, with the National Agricultural Research Project in Egypt dealing with the effects of land leveling precision and tillage practices on surface irrigation performance; from UMA Engineering to evaluate overshot gates as water measuring devices; from the Arizona Department of Water Resources and the USDI-Bureau of Reclamation to support the development of the Management Improvement Program; and from the USDI-Bureau of Reclamation to support a study in the Imperial and Coachella Valleys of Southern California to assess the use of Colorado River water in the area. The Department of Energy is supporting the ***CO_2-Climate Change Group*** program to evaluate the interactive effects of elevated CO_2 and increased temperature on plant growth and physiological processes including the development of predictive models. Temporary ARS funds help support the free-air CO_2 enrichment (FACE) project. The *New Crops Group* will receive support for three years through the USDA Alternative Agricultural Research and Commercialization Center for commercialization of Lesquerella; and for two programs supported jointly by DOD and the USDA/CSRS Office of Agricultural Materials: one, a two-year program to accelerate commercialization of vernonia, and the other to expand work on the extraction, characterization, and fabrication of guayule latex products for nonallergenic applications. A Cooperative Research and Development Agreement (CRADA) has been developed with a private company, in collaboration with the *Remote Sensing Group*, to focus on the application of remote sensing technology to farm management needs, including irrigation scheduling. We thank these many cooperators and will continue working to make these associations mutually beneficial in serving agriculture.

As always, we invite you to use this Annual Research Report. Let us know if there are questions or comments; all are invited and will be appreciated.

Allen R. Dedrick
Director

DEDICATION



Ray D. Jackson, Chief Scientist and Research Physicist, now Collaborator, at the U. S. Water Conservation Laboratory in Phoenix, retired in January 1993 after more than 35 years of service with the USDA's Agricultural Research Service. This Annual Research Report is dedicated to Ray for his impact on shaping the U.S. Water Conservation Laboratory as we know it today.

Ray is a Fellow of the American Association for the Advancement of Science, the American Society of Agronomy and the Soil Science Society of America. In 1986 he received the *USDA Distinguished Service Award*. Over the past two years, he was named *ARS Outstanding Scientist of the Year*, received the annual *William T. Pecora Award* for outstanding contributions to the understanding of the earth through remote sensing, was selected *Supervisor of the Year* by the Phoenix Federal Women's Program, and was honored as *Volunteer of the Year* by the Scottsdale, Arizona, Foundation for the Handicapped.

Ray. grew up on a small farm in Idaho during the Great Depression, the youngest of six children. He dropped out of high school twice, once to help his father who was incapacitated and, at age 16, to join the Marines. After three years, he was honorably discharged in 1949, obtained a GED certificate, and enrolled at Idaho State University. His education was interrupted when he was recalled to active duty to serve with the marines in Korea during the Korean conflict. Ray resumed college studies in 1953 at Utah State University, majoring in soil physics with dual minors in math and physics. He completed a Master's Degree at Iowa State University in 1957. ARS hired Ray that same year at Fort Collins where, in 1960, he received the first Doctor of Philosophy degree conferred by the Colorado State College of Agriculture.

Ray's work was multifaceted in that he was involved initially in soil physics and general heat and water transfer through porous media (1960s); he specialized in the estimation of crop evaporation rates (early 1970s), the use of temperature and reflectance measurements to determine plant water stress (late 1970s), and then in the 1980s, touched on nearly every aspect of the use of remote sensing for farm management. His contributions in all areas were singular.

Ray's accomplishments are documented in more than 300 published scientific articles and abstracts. To his credit, 158 different individuals have shared in his publications. At the "Remote Sensing of Soils and Vegetation" workshop which celebrated Ray's accomplishments on the occasion of his retirement, more than 60 participants made formal presentations with more than twice that many in attendance, including representation from nine foreign countries. One of the stated purposes of the workshop was to "bring together all the people who influenced Ray's scientific career and all the people who were influenced by Ray's research. Few scientists have touched as many lives and careers as Ray has." The event was indeed an outpouring of respect and love recognizing Ray's professional stature, but more important, his stature as a human being.

Ray, please accept the dedication of this report from all of us as a way of saying "THANKS."

U. S. WATER CONSERVATION LABORATORY
ORGANIZATIONAL DESCRIPTION AND MISSION STATEMENTS

The overall mission of the U. S. Water Conservation Laboratory is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric CO_2 on climate and yields and water requirements of agricultural crops.

The U. S. Water Conservation Laboratory research program is organized under two Research Units: Irrigation and Water Quality (I&WQ) and Environmental and Plant Dynamics (E&PD). I & WQ focuses on water management with emphasis on irrigation and water quality; E & PD concentrates on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Drs. Albert J. Clemmens and Bruce A. Kimball are the Research Leaders for the respective Research Units. The organizational structure for the USWCL is shown as Figure 1; and the entire USWCL personnel list in Table 1.

The mission of the Irrigation and Water Quality Research Unit is (a) to develop management strategies and tools (hardware and software) for the effective use of water and fertilizers in irrigated agriculture, and (b) to develop tools for the protection of groundwater supplies from degradation as the result of agricultural and urban waste management practices. The research unit takes a holistic approach to resolving water management problems within irrigation projects through research aimed at both farm and project operations and management and their interactions. Thus the focus is on identifying individual actions and practices that can have a positive effect on water quality and quantity overall. The unit also focuses on methods for resolving water supply and quality issues on a larger scale.

The mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies for meeting national agricultural product requirements within the context of possible changes in the global environment. Specifically, the Unit seeks (a) to develop new methods for assessing water and carbon dioxide fluxes in the soil-plant-atmosphere system, to quantify plant stress and its effect on crop yield, and to predict the effects of increasing carbon dioxide and climate change on plant growth and water use; (b) to develop suitable new and alternative crops capable of meeting national needs for renewable, agriculturally-based industrial products; and (c) to develop remote sensing and related tools for use in water conservation, irrigation scheduling, drought prediction and avoidance, and for monitoring crop conditions and assessing environmental change. All aspects of the program are designed to meet the challenges and opportunities imposed by dynamic environments, particularly those stressful to plants and their possible effects on crop production. A common thread uniting these efforts is the overall theme of increasing plant water use efficiency and conserving and improving the quality of agricultural water supplies. To attain these ends, the Unit is organized into a closely knit, multidisciplinary research group whose underlying philosophy is to devise multifaceted approaches to solving critical problems associated with the phenomenon of global environmental change.

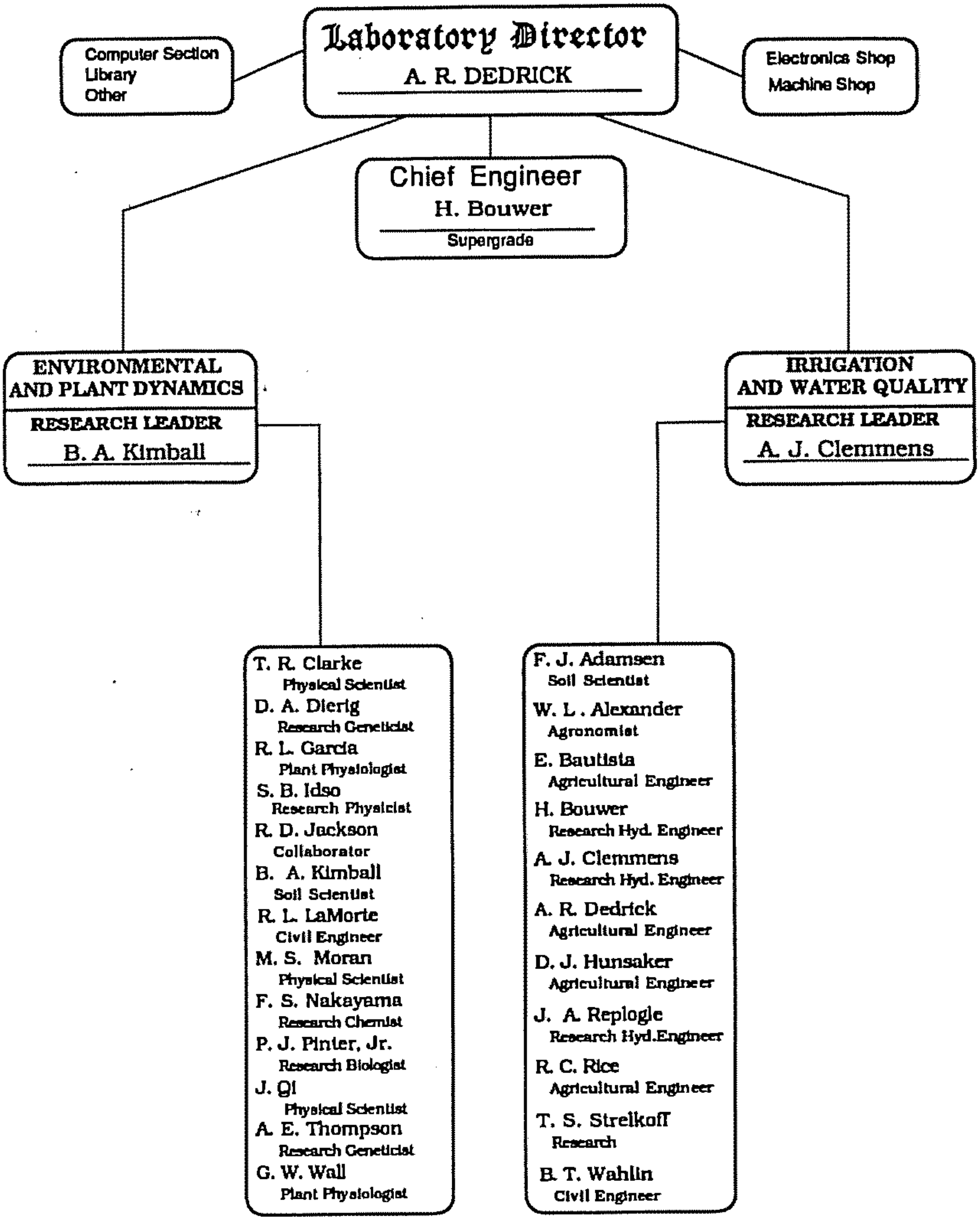


Figure 1. U. S. Water Conservation Laboratory Organization, December 31, 1993

Table 1. U. S. Water Conservation Laboratory Staff, December 31, 1993

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Alexander, William L.	Agronomist
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bailey, Benita L.	Secretary
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Research Leader and Supervisory Research Hydraulic Engineer
Coleman, David L.	Physical Science Technician
Dahlquist, Gail H.	Biological Laboratory Technician
Dedrick, Allen R.	Laboratory Director and Supervisory Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Eastman, Lynnette	Biological Technician (Plants)
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary
Heckart, Donna J.	Secretary
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Johnson, Stephanie M.	Biological Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Civil Engineer
Lewis, Clarence L.	Machinist
Martinez, Juan M. R.	Agricultural Research Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Physical Scientist
Nakayama, Francis S.	Research Chemist
Padilla, John	Engineering Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Powers, Donald E.	Physical Science Technician
Rasnick, Barbara A.	Physical Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Program Analyst
Rokey, Ric	Biological Technician
Salisbury, T. Lou	Office Automation Assistant
Seay, L. Susan	Publications Clerk
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist
Wall, Gerard W.	Plant Physiologist

TEMPORARY EMPLOYEES

Name	Title
Anderson, Kim	Research Associate (Resigned 12/31/93)
Baker, Michael	Research Assistant
Bautista, Eduardo	Agricultural Engineer
Bhattacharya, N.	Collaborator
Brooks, Talbot	Research Technician
Denaro, John	Research Technician
Franklin, Lorna	Senior Survey Interviewer
Freitag, Laurel A.	General Maintenance Mechanic
Gallagher, Daniel	Physical Science Aide
Garcia, Richard L.	Plant Physiologist
Gerle, Michael	Research Technician
Graham, Barry G.	Computer Clerk (Resigned 1/20/93)
Higgins, John D., Jr.	Biological Science Aide (Resigned 5/18/93)
Holmwood, Beth A.	Biological Aide (Resigned 6/15/93)
Husemann, Kevin	Biological Science Aide
Jackson, Ray D.	Collaborator
Johnson, Michael S.	Physical Science Aide (Resigned 11/27/93)
Klassen, Matthew F.	Physical Science Aide (Resigned 2/23/93)
Lacy, London P.	Biological Science Aide (Resigned 2/9/93)
Lazar, Bruce L.	Physical Science Aide (Resigned 11/27/93)
Leake, Gregory	Research Technician
Lemke, Kellie L.	Word Processor Operator
Newton, Anthony T.	Biological Science Aide (Resigned 5/4/93)
O'Brien, Carrie	Biological Aide
Ochs, Laura	Biological Science Technician
Oliveri, Jose	Research Laboratory Assistant
Qi, Jiagua	Physical Scientist
Reaves, Matthew L.	Physical Science Aide (Resigned 8/7/93)
Rebman, Jon P.	Biological Technician
Renfrow, Roger R.	Biological Science Aide (Resigned 5/16/93)
Shaw, Mary	Biological Science Aide
Sherrill, William	Biological Science Aide
Smith, Leslie	Research Technician
Strand, Robert J.	Engineering Aide
Strelkoff, Theodore S.	Research Hydraulic Engineer
Villalobos, Miguel A.	Research Assistant
von Schmidt, Baran	Computer Programmer Assistant
Wahlin, Brian	Civil Engineer

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LABORATORY SUPPORT STAFF

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MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE[1]

A.R. Dedrick, Supervisory Agricultural Engineer; E. Bautista, Agricultural Engineer;
S. A. Rish, Program Analyst; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Enhanced long-term management of water and other natural resources, grower profitability, and overall social well-being are essential to a sustainable irrigated agriculture. Because approaches to addressing these objectives are often uncoordinated and at odds with each other, all agricultural stakeholders--farmers, irrigation districts, and other agricultural support and regulatory organizations--need to interact proactively with each other and other interested parties to address these needs. To this end, the Management Improvement Program (MIP), a management process similar to those used to improve the performance of corporate organizations, is being applied to the business of irrigated agriculture. Since the technology transfer issues associated with strengthening irrigated agriculture are similar to those in other areas of agriculture and natural resource management, it is anticipated that the MIP will be widely applicable.

The purposes of this research are 1) to develop, apply, and refine for future use the Management Improvement Program (MIP) methodology; and 2) in each area in which a pilot MIP application is carried out, establish conditions for the continued improvement of farming practices and support services provided to farms by district and other irrigation related agencies.

The key outcomes expected in relation to the first of the above objectives (to develop, apply, and refine the MIP) are, first, a generic MIP model and guidelines for its effective use in different agricultural settings, developed through several pilot MIPs. Secondary outcomes include (a) testing the effectiveness of the MIP as a vehicle for promoting technology transfer with interorganizational and interdisciplinary support; (b) testing the effectiveness of the MIP as a vehicle for responding to relevant issues; (c) using what is learned to strengthen other USDA-ARS research activities; and (d) identifying a range of settings in addition to irrigated agriculture in which the MIP might provide significant impact.

Outcomes related to the second purpose of the research (to achieve direct local impact through each MIP application) include (a) reaching a comprehensive current understanding of the performance of irrigated agriculture in the pilot area and of opportunities for management improvement; (b) improving communication and collaboration among farmers, irrigation district, and government agencies, resulting in strengthened program planning and working relationships; (c) identifying and selecting alternative actions and implementing programs to strengthen the performance of irrigated agriculture through improved resource management, with farm profitability and sustainability the goal; and (d) establishing the local institutional support for the MIP's continued application.

APPROACH: In December 1990, under the direction of the U. S. Water Conservation Laboratory, an Interagency Management Improvement Program (IMIP) was initiated. The collaborating agencies stated an interest in the potential of the MIP to support improved irrigated agricultural productivity, profitability, and natural resource management; and appointed an oversight IMIP Coordinating Group (IMIP-CG), Table 1. The first major step in the overall assessment of the MIP was to be a pilot application, currently nearing completion in cooperation with the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in central Arizona. Efforts during 1991, 1992, and 1993 have focused on this first pilot, the MSIDD-Area MIP.
Milestones in the MSIDD-Area MIP during 1993 (see 1990, 1991, and 1992 "Annual Research Reports" for milestones during those years) include

1) <u>Completion of the Management Planning Phase and initiation of the Performance Improvement Phase of the MIP (2/93)</u>. Programs were developed and initiated relative to (a) providing overall coordination of MIP-related activities (Interim Coordinating Group described in milestone 2); (b) improving on-farm profitability and sustainability; and (c) reducing the impact of water costs and assessments, and other related issues. In all instances, the workgroups established to carry out the planning activities included growers from the MSIDD area

[1] The Management Improvement Program Team (MIPT) includes Dedrick, Bautista, and Rish of the USWCL; and consultants W. Clyma (MIP Specialist) and D. B. Levine (Management/Team-Building Specialist).

and representatives of government organizations supporting or regulating agricultural activities in the area. MSIDD-Area MIP program areas and titles are presented in Table 2.

2) <u>Establishment of an Interim Coordinating Group (ICG)</u>. Development of local leadership is essential for the continued cooperation of MSIDD-Area growers and associated agencies and coordination of programs resulting from MIP intervention. As the first area-wide coordination of growers and agriculture-related services, the ICG provides that leadership and also an open forum for information sharing and problem identification and resolution. Current ICG membership is shown in Table 3.

3) <u>Initiation of MIP Evaluation</u>. An evaluation of the MSIDD-Area MIP was initiated to assess the success of the research program (i.e., what was the current and anticipated future impact of the process, and what can be learned from the first application of the MIP to guide future applications). The evaluation strategy relies on interviews with participants and explores the impact of the process both quantitatively and qualitatively.

FINDINGS: The Diagnostic Analysis of the MSIDD-Area MIP identified strengths of the agricultural system and opportunity areas for improving low performance and sustaining high performance. These findings have led to comprehensive interorganizational and interdisciplinary program planning and implementation. The programs address many of the low performance areas identified in the Diagnostic Analysis and, hence, have the potential to enhance the profitability and sustainability of agriculture in the area. A local coordinating group, the ICG, was formed, and a local grower was selected to lead its efforts. ICG membership criteria require that members have direct responsibility for the geographical area that includes at least all of the MSIDD and have authority to deploy resources in a problem-solving, flexible, and adaptive way. The ICG's shared commitment to continue the MIP approach (i.e., effecting and managing change) in the MSIDD area and to "make a difference" as a group is reflected in the ICG Charter and Mission Statement, one of the first accomplishments of the organization.

INTERPRETATION: As stated in the 1992 "Annual Research Report," the interdisciplinary approach of the MIP departs from traditional, single-disciplinary problem-solving and strives for a real-world understanding of performance. The ICG, as an important piece of the pilot MIP, has been carefully constituted and chartered to assure the ICG's and MIP's future impact. Early indications, with assumption of leadership by a local grower and the expressed commitment of the ICG membership, are that the ICG will be sustainable as long as there is a need. A range of indicators show that the overall approach used in the pilot MIP has been conducive to accurate problem identification, improved interorganizational communication and collaboration among growers, district and agencies; and to the development of programs focused on the needs of the local irrigated agricultural system. The pilot MIP is also serving well in providing the foundation for appropriate MIP model assessment and refinement. Continued interest in the MIP process has led to formal and informal discussions regarding use of the MIP process with the Bureau of Reclamation, EPA, Western Area Power Authority, Arizona Public Service, SCS, and ASCS. The bringing together of various entities in a proactive, nonconfrontational way was a topic for presentation at the ARS Pacific West Area Research Leaders' meeting in November 1993.

FUTURE PLANS: The pilot MIP will be completed in January 1994. The evaluation results, available in early 1994, will lead to final model refinement and documentation by the MIP Team. Documentation of the MSIDD-Area MIP will include a series of peer reviewed articles as a single issue of the international *Irrigation and Drainage Systems Journal* is scheduled during 1994. Further documentation will include a concise report of the MSIDD-Area MIP, and finally, whatever documentation is required to define the refined model adequately. An application of the refined MIP model will be investigated with interested parties under the guidance of the IMIP-CG.

COOPERATORS: Cooperators in the MIP include all entities listed in Tables 1 and 3, as well as Colorado State University. Funding has been provided by ARS, USBR, SCS, and the ADWR; significant in-kind contributions have been made by all involved.

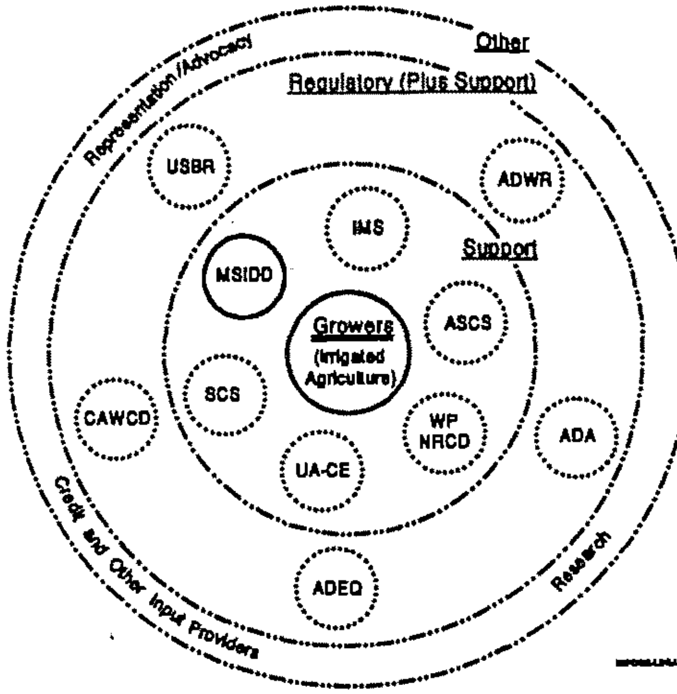

Figure 1. Schematic representation of entities involved in the pilot *MSIDD-Area MIP*. Entities are included because of their potential to impact irrigated agriculture in the area. Profitability and sustainability of irrigated agriculture is the goal of the pilot MIP; therefore, growers are the main focus of the program and are shown appropriately in the center. Organizations directly supporting agriculture are represented in the next circle level; followed by regulatory organizations; with research, political, and financial entities shown in the outer circle. The solid circles around the MSIDD and Growers depict the entities that were studied in depth in the MSIDD Diagnostic Analysis. The other organizations became fully involved during Phase II, the Management Planning Phase.

Table 1. The Interagency Management Improvement Program Coordinating Group has responsibilities to (a) oversee and manage the program to determine the potential of the MIP, (b) represent each organization's interest in the applicability of the MIP, and (c) develop recommendations for long-term MIP use and accessibility.

REPRESENTATIVE	AGENCY AND POSITION
Al Dedrick	USDA-Agricultural Research Service, U.S. Water Conservation Laboratory, Laboratory Director and MIP Project Leader[1]
Tom Carr	Arizona Department of Water Resources, Asst. Deputy Director[1]
Bob Crawford	USDA-Soil Conservation Service, State Resource Conservationist[1]
Jim DuBois	Arizona Department of Environmental Quality, Hydrologist[1]
John Hagen	Arizona Department of Agriculture, Deputy Director
Steve Jones	Water Conservation & Advisory Center, USDI-Bureau of Reclamation, Lower Colorado Region, Coordinator[1]
Peter Wierenga	Department of Soil and Water Science, University of Arizona Cooperative Extension[1] and College of Agriculture, Head

[1]Founding Member Agencies.

Table 2. MSIDD-Area MIP Programs.

PROGRAM AREA	PROGRAM TITLE
Overall MIP Guidance, ICG Activities	• Program Coordination and Support • Area-Wide Communications, and MIP Input and Feedback • "Single Stop Shopping" for Technical Support and Program Availability Information
On-Farm Program 1: Improving Soil and Water Resource Management	• Farm-Specific Assistance Program (FSAP) • Education Prog. 1: Opportunities for Strengthening On-Farm Profitability and Sustainability • Education Prog. 2: Grower-to-Grower Networking • R&D Prog. 1: Reduction of Flow Fluctuations in Irrigation Laterals • R&D Prog. 2: High and Low On-Farm Water Usage • R&D Prog. 3: Potential for Minimum or No-Tillage Practices in Central Arizona
On-Farm Program 2	• Supporting Commodity Diversification in Central Arizona
Water Costs, Assessments, and Related Issues	• Reducing the Level and Impact of Water Costs and Assessments

Table 3. MSIDD-Area MIP Interim Coordinating Group.

REPRESENTATIVE	ENTITY AND POSITION
Gary Butler	Leader and Grower
Carlos Carranza	Grower
Loren Pratt	Grower
Van Tenney	MSIDD, General Manager
MacD Hartman	West Pinal NRCD, Chair and Grower
Dennis Kimberlin	ADWR, Pinal Active Management Area, Director
Buddy Ekholt	Irrigation Management Service, Director
Ralph Ware	USDA, SCS, District Conservationist, Pinal County
Cliff Neal	Central Arizona Water Conservation District, Engineer/Hydrologist
Tom Burbey	USDI, Bureau of Reclamation, Arizona Projects Office, Chief, Water and Lands Division

IRRIGATION INDUSTRY/ARS COLLABORATIVE EFFORT[1]

A.R. Dedrick, Supervisory Agricultural Engineer; and
D.F. Heermann, Supervisory Agricultural Engineer

PROBLEM: Although there have been some impressive partnerships between the Irrigation Industry and ARS, they had never joined in a concerted, sustained effort to impact irrigation on a broad scale up through the national level. In May 1991, in a workshop setting, an effort was launched by representatives of the Irrigation Industry and ARS to develop a framework within which the two entities could establish a collaborative program to address issues facing irrigation as a whole. Thus, the "Collaborative Effort," led by Dedrick and Heermann, was initiated with its stated purpose

> For the Irrigation Industry and the Agricultural Research Service to foster and focus an ongoing partnership in support of irrigation that yields optimal societal benefit.

APPROACH: In the May 1991 workshop, over 40 attendees, almost evenly divided between the Irrigation Industry and ARS irrigation and drainage researchers, Table 1, met to clarify various missions and current programs, to identify irrigation's priority research needs, to clarify areas and procedures offering significant collaborative opportunities, and to decide how best to continue workshop initiatives. At that meeting, a Leadership Group, again co-chaired by Dedrick and Heermann, was mandated to lead the Collaborative Effort. Over the last two-and-a-half years, the Leadership Group has guided actions to address the agenda that emerged from the workshop, including semiannual meetings to adjust overall Collaborative Effort plans and to review and support its three Leadership Group subgroups, each of which focuses on one of three main thrusts, Table 2:

- Supporting the Irrigation Association (IA) as a key representative of the Irrigation Industry in identifying priority irrigation related research needs and communicating them to the research community,
- Increasing the amount of collaborative research carried out by Irrigation Industry and ARS scientists and engineers, and
- Proposing and supporting a study by the Water and Science Technology Board (WSTB) of the National Academy of Sciences/National Research Council focusing on the future of irrigation in the United States.

FINDINGS: Key results of the Collaborative Effort over the last two-and-a-half years include

- Identification of Priority Research Needs. In a July 1992 meeting with the Irrigation Association, the Leadership Group proposed to the IA Board of Directors an action plan by which the IA could identify priority research needs of the industry and update them annually. The Board of Directors unanimously approved a plan to establish a Research Committee within IA to identify priority research needs and provide them to the ARS on a regular basis. The Committee will prioritize research needs identified and submitted by the IA Divisions.
  At the 1992 IA Exposition in New Orleans, IA Division Leaders identified an initial list of five major "Research Opportunity" areas of thirty-two items, Table 3. In September 1993, IA and ARS representatives met to discuss these Research Opportunities which address research needs for all of irrigation, including turf and landscape, in relation to ARS's ongoing program planning process. Attendees included IA representatives President Bill Koonz, incoming president Joe Goecke, and Executive Director Charles (Pepper) Putnam; and ARS representatives Acting Administrator Essex Finney, Jr., Associate Deputy Administrator Jan van

[1] Dedrick and Heermann (Irrigation and Drainage Research Unit, Ft. Collins, Colorado) have co-chaired the Collaborative Effort. Key input to the process has been provided by J. A. Chapman, Valmont Industries, Valley, Nebraska; L. E. Stetson, ARS, Lincoln, Nebraska; and S. A. Rish, ARS, Phoenix, Arizona, as Subgroup Co-Chairs; T. A. Howell, ARS, Bushland, Texas, for development of the "Yellow Pages"; and consultant D. B. Levine (Management/Team-Building Specialist) for overall facilitation of the Collaborative Effort.

Schilfgaarde, and National Program Leader Dale Bucks. The meeting is viewed as the initiation of a longer-term process for conveying Irrigation Industry research needs to ARS.

- Increasing the Amount of Collaborative Research Carried out by ARS and the Irrigation Industry. Activities in this area have focused on increasing the awareness of Irrigation Industry and ARS scientists and engineers about opportunities for collaborative research. Specific accomplishments include a "Yellow Pages" directory of ARS Irrigation and Drainage researchers, their areas of research, accomplishments, and publications (over 500 copies distributed to date); a Collaborative Effort exhibit at the last three IA Expositions to gain visibility and provide information on collaborative research (support provided by IA and the ARS Offices of Technology Transfer, Interactive Cooperation, and Information); a first-steps "how-to" brochure for entering into Cooperative Research and Development Agreements (CRADAs); and publicity on Collaborative Effort initiatives through news releases and mailings.
- Proposing and Supporting the Water Science and Technology Board Irrigation Study. The need to provide an objective, unbiased description of irrigation's present position--its value, problems, and opportunities--to the public was the topic of considerable discussion at the May 1991 workshop. The Leadership Group developed and presented a statement of work for a proposed study on "The Future of Irrigation in the Face of Competing Demands and Water Quality Constraints" to the National Academy of Sciences, Water Science and Technology Board (WSTB), in November 1991. The WSTB agreed in early 1992 to undertake the study. The Leadership Group has worked closely with the WSTB to provide appropriate input and support to a range of WSTB activities related to the study, including reviewing numerous drafts of the program of work, identifying potential funding sources, providing nominations for the Study Committee, and continuing liaison between the Leadership Group and the Study Committee. The Study has been initiated, with the first meeting of the Committee in October 1993. The Study will take 24 months and will result in a report to be made available to the public and other interested parties. Reports from WSTB studies provide an in-depth analysis of the issues and impacts of various strategies or policies, and they are used in many instances for policy and political decisions. The Study is funded by the Irrigation Association, USDA/ARS, USDI/Bureau of Reclamation, Ford Foundation, and Idaho Power Association, each of whom also provides a liaison to the process.

INTERPRETATION: The enthusiastic willingness of representatives from both the Irrigation Industry and ARS to work toward the Collaborative Effort goals has produced a number of significant accomplishments. The efforts toward collaborative (Yellow Pages and CRADAs) and ARS-specific research (Research Priorities) have initiated important ongoing interaction between ARS and the Industry. It is the consensus of the Leadership Group that the WSTB Study will provide a cornerstone for the future of irrigation in the United States. The Collaborative Effort has been a successful experience in building ongoing interaction, understanding, and trust between a client group, in this case the Irrigation Industry, and ARS. The approach used has potential as a model for building partnerships between ARS and other client groups.

FUTURE PLANS: The Leadership Group last met in September 1993. Future efforts will include "seeing through" or maintaining activities already initiated. For the Priority Research Needs, this will require input as appropriate to assist the IA in institutionalizing the process the Research Committee will use for its regular development and provision of priority research needs to the ARS and others, as well as appropriate support to ARS as follow-up to the IA's submissions. For Increasing Collaborative Research, guidelines for continuation of the Collaborative Effort exhibit at the IA Expo will be developed, the exhibit at the Expo will be continued on an annual basis, and the Yellow Pages will be updated periodically and distributed by IA and ARS Headquarters. In addition, a pilot workshop on collaborative research is being considered to introduce industry product engineers to CRADAs and other opportunities for collaboration. The liaison between the Collaborative Effort and the WSTB Study will be maintained, with input provided by the Leadership Group as appropriate. Future meetings of the Leadership Group, as well as adjustments of membership and focus, will depend on progress of the ongoing activities and the requirements of newly identified activities appropriate to the Collaborative Effort's goals.

COOPERATORS: Representatives of the Irrigation Industry and ARS shown in Table 1.

Table 1. May 2-3, 1991, workshop participants.

Industry Representatives

Robert A. Anderson, Spectra-Physics, Dayton, OH
James D. Anschutz, Netafim Irrigation, Fresno, CA
James E. Burks, Waterman Industries, Exeter, CA
Ronald Campbell, Omnidata International, Logan, UT
John A. Chapman, Valmont Industries, Valley, NE
James P. Craft, Conservation Technology Ser., Irvine, CA
Richard E. Hunter, Hunter Industries, San Marcos, CA
Leslie W. Jochens, Western Irrig. Supply House, Englewood, CO
John M. Mylne III, Toro, Riverside, CA
Barton R. Nelson, Nelson Irrigation, Walla Walla, WA
William R. Pogue, Irrometer Company, Riverside, CA
Rodney Ruskin, GEOFLOW, San Francisco, CA
Robert C. Sears, Formerly IA, Arlington, VA
Harry Sullivan, Senninger Irrigation, Orlando, FL
Glenn O. Tribe, Cornell Pump, Portland, OR

Representatives of End Users

Dana B. Fisher, Fisher Ranch, Blythe, CA
Thomas E. Levy, Coachella Valley Water District Coachella, CA
Daniel G. Nelson, San Luis Water District, Las Banas, CA
John R. Norton III, J. R. Norton Co., Phoenix, AZ
Kenneth H. Solomon, CIT, Fresno, CA
Michael D. Stortz, Tri-State G&T Assoc., Denver, CO
Earl Tankersley, Franzoy-Corey Engineering, Phoenix, AZ
Richard J. Wenstrom, Pumping Plant Testing, Kinsley, KS

ARS Representatives

Headquarters
Jan van Schilfgaarde, National Program Staff
Dale A. Bucks, National Program Staff
James T. Hall, Office of Cooperative Interactions
Arizona
Allen R. Dedrick, U. S. Water Conservation Lab.
John A. Replogle, U. S. Water Conservation Lab.
California
Claude J. Phene, Water Management Research Lab.
Robert J. Reginato, Hq Pacific West Area
Colorado
Harold R. Duke, Irrigation and Drainage Research
Dale F. Heermann, Irrigation and Drainage Research
James R. Welsh, Great Plains Systems Research
Georgia
Clyde C. Dowler, Nematodes, Weeds and Crops Research
Idaho
Allan S. Humpherys, Soil/Water Mgmt. Research
Dennis C. Kincaid, Soil/Water Mgmt. Research
Louisiana
James L. Fouss, Soil and Water Research
Nebraska
LaVerne E. Stetson, Soil/Water Conservation Res.
North Dakota
Todd P. Trooien, Soil, Water & Crop Management Res.
South Carolina
Carl R. Camp, Soil and Water Conservation Research
Texas
Terry A. Howell, Conservation and Production Res. Lab.
Jack T. Musick. Conservation and Production Res. Lab.
Washington
Ronald E. Yoder, Soil and Water Management Research

Table 2. The Collaborative Effort Leadership Group and various subgroups.

Supporting IA in Identifying Research Priorities	Increasing the Amount of Collaborative Research	Supporting the WSTB Irrigation Study
Dale Heermann, Co-Chair	LaVerne Stetson, Co-Chair	Al Dedrick, Chair
John Chapman, Co-Chair	Shirley Rish, Co-Chair	Tom Levy
Dale Bucks	Terry Howell	Bill Pogue
Bart Nelson	Dick Hunter	Pepper Putnam
Jim Welsh	Joe Lord	Rodney Ruskin
		Ken Solomon

Table 3. Irrigation Industry priority research needs/opportunity areas developed and presented to ARS in September 1993.

Opportunity Area	Subtopics
• Determine irrigation regimes (type of system, frequency, amount, method of application) that most effectively use water and crop production chemicals for specific crops, field, climatic, and soil conditions.	Economics, environmental issues, energy efficiency, temperature control, operator safety, limited water supply, data base development, use- and crop-specific water requirements (turf, ornamental, agricultural), and wind effects
• Develop environmentally sound manufacturing, recovery, and recycling techniques for irrigation system components.	Manufacturing process and disposition and system components
• Develop economical irrigation technologies for the utilization of biological/chemical wastes to prevent environmental degradation.	Rural, municipal, and industrial waste; food processing; agricultural waste; management of waste disposal; aesthetic considerations; and control of air and water pollution
• Standardize evaluation guidelines for performance and management of all irrigation systems (turf, ornamental, agriculture).	Uniformity of water application, economic and environmental optimization of chemical application, seasonal vs. single-event evaluation, total area vs. inappropriate subsets, long- vs. short-term performance, equipment life, interchangeability/compatibility, materials suitability, development of ANSI/ISO/EC standards
• Adapt and promote adoption of new technologies by today's irrigation community, consistent with current economic and environmental constraints (holistic approach).	Computer technology, automated control, field and remote sensors, cost effective communication systems, geographic information systems (GIS), global positioning systems (GPS)

IRRIGATION FLOW MEASUREMENT STUDIES

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: Water flow measurement continues to be a major tool for improving irrigation water management to conserve water and energy in irrigated agriculture. Problems with flow rate devices include their relative complexity, required training level of field users, and economics of installation and operation. Other problems include pipeline flows that take their water from canals and can carry trash unsuitable for propellers or other meters. Yet a further problem involves sensing a water surface reliably, economically, and accurately, and in a way that is compatible with data acquisition and control systems.

APPROACH: Several measuring techniques, some historically well known but little used, are being evaluated with a view to updating them in the light of modern understandings of fluid dynamics and advances in secondary instrumentation. A general approach to evaluating all measuring devices involves carefully constructing or preparing test items for comparison of their flow rate to that of a calibrated standard device. This approach is supplemented by further evaluations of general hydraulic behavior as predicted by hydraulic theory. Devices currently active or previously mentioned as being under study are

(a) Venturi meters fabricated from standard plastic pipe parts and calibrated against the laboratory weigh-tank system;
(b) Multiple floats simultaneously dumped across lined, trapezoidal channels above a starting point and the leading particle at each station, not necessarily the same particle, timed over a selected travel distance;
(c) A vane-type flow meter configured as a triangular blade, the force on which can indicate discharge rate in rectangular channels, independent of flow depth;
(d) Verification of the free flow measuring and submerged flow indication characteristics of the Clausen Weir Rule, used in the Southwestern United States for over two decades;
(e) Propeller meters for trash-filled flows;
(f) Rising bubble technique for measuring flows in ill-defined earthen channels; and
(g) Overshot gates used for both measurement and control (reported under separate study).

FINDINGS:

(a) The Venturi meter study has been completed. Plastic pipe fittings of the kind usually used by the irrigation industry can be fashioned into suitable Venturi meters with an expected accuracy of $\pm 2\%$, not including the errors of the readout method.

(b) Analysis of data sets for six canals of widely varied sizes and new data from 3 other canals support the rationale that a reasonably well defined relationship involving absolute roughness and the most rapid surface-velocity filament does exist. Figure 1 indicates a linear relationship between the ratio of maximum surface velocity and the average channel velocity (Vr on the y-axis), and the ratio of the absolute roughness, Kr, with the hydraulic radius Rh (Kr/Rh on the x-axis). Methods to improve the characterization of Kr are being studied.

(c) No further studies were done on the triangular blade during this reporting period. A smaller force cell has not yet been budgeted.

(d) The most apparent feature of the Clausen Weir Rule is how it averts the necessity of dealing with a velocity of approach. The form of the equation on which it appears to be based is in terms of total head at the weir overfall, which already includes the velocity of approach adjustments. Some literature review on methods of handling weir flow in submerged conditions was completed, but a definitive analysis has not been accomplished.

(e) Development of design concepts for the clog resistant propeller meter for the large pipes frequently found in irrigation practice (larger than 2-feet diameter) was completed. Commercialization efforts appear to be in order.

(f) The rise velocity of bubbles must be known for the rising-bubble technique and was measured in a special tank for a variety of bubble sizes. Uniform large bubbles appear to dominate most nozzle releases and are sufficiently constant in the range of interest to meet requirements of the intended applications. It is fortuitous to the technique that smaller, slower-rising bubbles are simply swept downstream and do not cloud observation of the bubble fringe on the water surface. Additional lab uses for the bubble system include flow visualization to evaluate the uniformity of the velocity patterns upstream and downstream of devices being tested.

(g) The adjustable flume of Patent No. 5,156,489, granted on October 20, 1992, may find application as an alternate to handle accurately submerged flow for the overshot gates.

INTERPRETATION:

(a) The suitably accurate and economical plastic-pipe Venturi meters should find wide application in irrigation systems, particularly those using gated pipe. Costs per meter are about $120 for the pipe and fittings, plus about 2 hours of labor. Individual calibration is not required.

(b) Based on the hydraulic radius, Rh, and reasonable handbook values for channel roughness, n, which can be converted to absolute roughness, Kr, the ratio of average channel velocity to maximum surface velocity, Vr, can be established as a function of Kr/Rh. This appears to reduce the uncertainty in the float method to about $\pm$ 5% from a previous uncertainty of $\pm$ 15%.

(c) Properly shaped vanes, or blades, used as a fluid drag body can indicate flow rate per unit width without specific knowledge of flow depth, if the horizontal force can be measured.

(d) Properly used and on an appropriate sharp weir crest, the weir rule functions satisfactorily for many irrigation measuring activities when flow was free overfalling. Against weighed discharge rate, it is about 2% too high. Submerged flow accuracy has yet to be evaluated.

(e) A propeller meter configuration and readout method has been devised that deviates from previous concepts being manufactured and may lead to an economical general purpose, trash-resistant, propeller meter adaptable to many large pipe sizes, with a readout method that will be economical, reliable, and capable of indicating flow rate and total volume of irrigation water delivered.

FUTURE PLANS:

(a) A manuscript on the plastic-pipe Venturi meters has been accepted for publication. Future work, though of low priority, may include generalizing the loss predictions as was done for the long-throated flumes, so that more flexibility in sizes, fittings and lengths can be provided.

(b) The data sets on canals have recently been extended. These data have provided the impetus to specially design equipment and methods to evaluate accurately channel roughness in field channels.

(c) The force meter will be further evaluated for its expected functions, using a smaller force cell, yet to be selected. Attempts to extend it to serve as a weir-overfall measuring device will be investigated. There is evidence that it might function as an advanced "weir rule."

(d) The submerged flow functions of the Clausen Weir Ruler will be investigated and a suitable theoretical basis sought to better understand the limitations and extensions of the method.

(e) A prototype model of the propeller meter for trashy flows will be attempted through Cooperative Research and Development Agreement (CRADA). The prototype will be installed in a field situation in 30-inch diameter irrigation delivery pipeline to evaluate field maintenance and operational lifetime expectations.

(f) A bubble-curtain flow measuring technique that has field utility, particularly for otherwise difficult-to-measure earthen channels, will be evaluated. Field equipment has been built.

(g) A Parshall flume has been acquired for study to evaluate proposed field modifications to make them behave as long-throated flumes to increase range of free flow operation.

(h) A special commercial water depth sensor, using special sonic shock wave generation and detection, will be evaluated for irrigation applications.

COOPERATORS: There are no formal cooperators on these projects. Parties that have expressed specific interest include the Soil Conservation Service, various irrigation districts, and irrigation consultants.

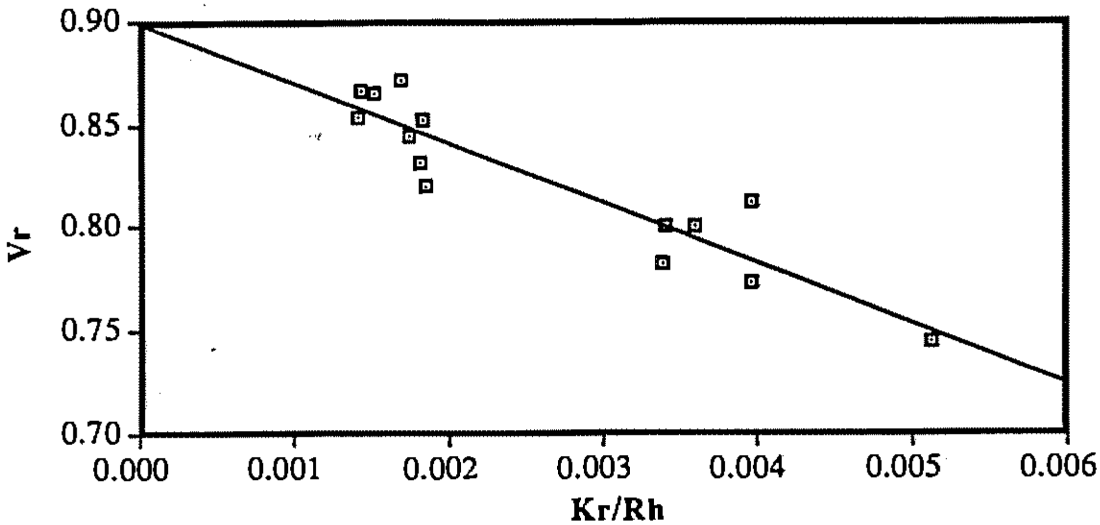

Figure 1.

Figure 1. Relationship between absolute roughness and maximum surface velocity.

HIGH-FREQUENCY, SMALL VOLUME LEVEL BASIN IRRIGATION FOR COTTON

D.J. Hunsaker, Agricultural Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; and W.L. Alexander, Agronomist

PROBLEM: Properly managed level basin irrigation systems designed to apply light, frequent water applications may increase cotton yields and reduce on-farm water use. In the Southwest, where cotton is a major crop, irrigation is accomplished predominantly with surface methods. Traditionally, surface irrigation systems are designed and managed to minimize irrigation frequency, resulting in a large volume of water applied during each irrigation. This approach tends to minimize labor and energy costs and allows the grower to maximize field lengths. However, irrigations scheduled at long intervals practically assures some degree of water stress during the growing season. Studies conducted in Arizona in recent years have demonstrated a significant yield advantage by increasing the frequency of water applications to cotton. The most critical period to avoid water stress and lint yield reduction is during peak fruiting, according to some investigations.

In addition to potential yield benefits, ability to provide light applications could reduce water use requirements and decrease nutrient and fertilizer losses from excessive deep percolation. Light irrigation applications (e.g., seed germination, early season development, fertilizer applications, etc.) are often desirable but difficult to attain with surface systems designed to apply large volume irrigation. Typically, field conditions early in the season make over-application unavoidable.

Level basin irrigation is a viable surface irrigation method capable of attaining uniform and efficient applications of water, although extremely light applications (2 or 3 cm) are probably not feasible unless fields are extremely small. However, our experiences using farm-scale level basins (14 m by 250 m) have indicated that uniform applications may be attainable with gross water applications of about 7 cm. Lighter applications may be possible if furrows are smoothed and compacted and irrigation frequencies are increased.

The objectives of this research are to evaluate level basin design and management procedures for applying high-frequency, small volume irrigation and to evaluate the economic feasibility of this irrigation approach for growing cotton in the southwestern United States.

APPROACH: Initial irrigation field studies were conducted in 1993 to evaluate various management factors and field conditions as they affect high-frequency, small volume irrigation. Some of the key factors studied were (1) seasonal and spatial variations in furrow intake rate as affected by irrigation frequency, antecedent moisture, and soil compaction; (2) furrow advance rates as affected by basin inflow rate and irrigation volume, irrigation frequency, furrow roughness, and soil compaction; and (3) the limit on application depth as intake rates, soil moisture and flow resistance change through the season. Results from the 1993 irrigation studies will be used to develop level basin design and management procedures for implementing high-frequency, small volume irrigation.

The irrigation studies were conducted on a 2-ha, precision-leveled, Mohall sandy loam field site at The University of Arizona Maricopa Agricultural Center. After constructing conventional cotton beds (1.0-m row spacing), the field was separated into five experimental basins separated by border dikes. Each basin was 12 rows wide and 250 m long. Rectangular canal gates, installed at the head of each basin, controlled the irrigation water delivery from a concrete-lined open channel. The irrigation inflow rate delivered to the basins was measured in the open channel with a broad-crested weir located upstream from the basins. Furrows within each basin were interconnected at the tail end of the field.

The irrigation management characteristics for the five basins were (1) low-frequency, large volume, irrigation with a moderately high basin inflow rate (~ 85 lps) and no compaction or smoothing of furrows (LMN); (2) high-frequency, small volume, irrigation with a moderately high basin inflow rate and no compaction or smoothing of furrows (HMN); 3) high-frequency, small volume, irrigation with a moderately high basin inflow rate and compaction and smoothing of furrows (HMC); (4) high-frequency, small volume, irrigation with a high basin inflow rate (~ 125 lps) and no compaction or smoothing of furrows (HHN); and (5) high-frequency, small volume, irrigation with a high basin inflow rate and compaction and smoothing of furrows (HHC).

Furrows within HMC and HHC basins were smoothed and compacted using a weighted metal device shaped like a torpedo which was dragged through the field by a tractor in early April 1993, prior to preplant irrigation, and again during normal cultivation procedures in May and June. All basins were given at least 110 mm of preplant irrigation during April 6-9. A short staple cotton cultivar with a relatively determinant fruiting pattern, Deltapine-20 (DP-20), was planted in all basins on April 23.

Irrigation scheduling was based on the soil water balance method using AZSCHED, a computer model developed by the Department of Agricultural and Biosystems Engineering, The University of Arizona. The model predicts the date and irrigation depth to be applied using weather data obtained from a nearby meteorological station for a specified management allowed depletion (MAD). Basins under high-frequency irrigation were irrigated for a MAD level of 30%, and the basin under low-frequency irrigation was irrigated at a 55% MAD.

Data collected in 1993 included soil water content before and after irrigation, furrow intake rates prior to irrigation for adjacent wheel and non wheel furrows at three locations in the basin, furrow advance times in each furrow of a basin, infiltration opportunity times at several locations in the basin, individual furrow flow rates, and surface water profile in an individual furrow within each basin. Cotton yield data were obtained by machine harvesting two central rows of each basin on October 8, 1993. Harvested yields were obtained in 7.5-m length increments over the entire length of row.

A companion field study on cotton yield response to high-frequency irrigation was carried out on a small adjacent field. DP-20 was planted on April 9, 1993, and grown under three irrigation regimes: (1) low-frequency (55% MAD), (2) high-frequency (30% MAD), and (3) low-frequency (55% MAD) with high-frequency (30% MAD) during peak fruiting. Treatments were replicated six times in plots having 8 rows of cotton, 10 m long. Destructive samples were collected weekly between June and August for determining plant development during the season. Two undisturbed cotton rows were machine-harvested in all plots on September 16.

FINDINGS: The largest effects on furrow advance due to soil smoothing and compaction were observed during the preplant irrigation and the first irrigation after crop establishment. Full furrow advance time and gross application depth (Fig. 1) were about two times greater for the non compacted LMN basin compared to the compacted HMC basin during the preplant irrigations (April 6-9), as well as during the next irrigations in May (data not shown). Uniformity of advance for wheel and non wheel furrows were also greatly improved early in the season when furrows were smoothed and compacted. By mid-season, advance rates in all basins under high-frequency were about the same, regardless of inflow rate or furrow compaction. By mid-July (peak fruiting), application depths on the order of 60-80 mm could be applied in all high-frequency basins. Analyses on furrow intake and water application distributions are in process.

Figure 2 summarizes water use and yield data for the three irrigation regimes of the small plot study. High-frequency treatments required about 40 mm more irrigation water than the low-frequency treatment due to increased evapotranspiration (as measured by soil water depletion) during peak fruiting. Above-ground plant biomass (measured on August 18) and final lint yields under high-frequency irrigation for the entire season and high-frequency irrigation during peak fruiting were 18-21% and 11-15% higher than that obtained under low-frequency irrigation, respectively. Lint yield mean comparisons between the high-frequency and low-frequency irrigation regimes were significant at the 10% confidence level.

INTERPRETATION: Devices to smooth and compact furrows, such as the torpedo device used in this study, could increase water conveyance across furrows in level basins. The advantage of faster advance times should be particularly significant during early season irrigations when light applications are desirable. Light, frequent applications to cotton during peak fruiting may increase yields and appear to be possible even in sandy loam soils with properly designed and managed level basins.

FUTURE PLANS: Development of high-frequency, small volume irrigation will continue. Future work includes plans to implement a second irrigation study in 1994 to test yield response to high-frequency irrigation in large basins. Information obtained during the initial studies will be used to develop management approaches for efficient, frequent water applications.

COOPERATORS: D.D. Fangmeier, Department of Agricultural and Biosystems Engineering, The University of Arizona.

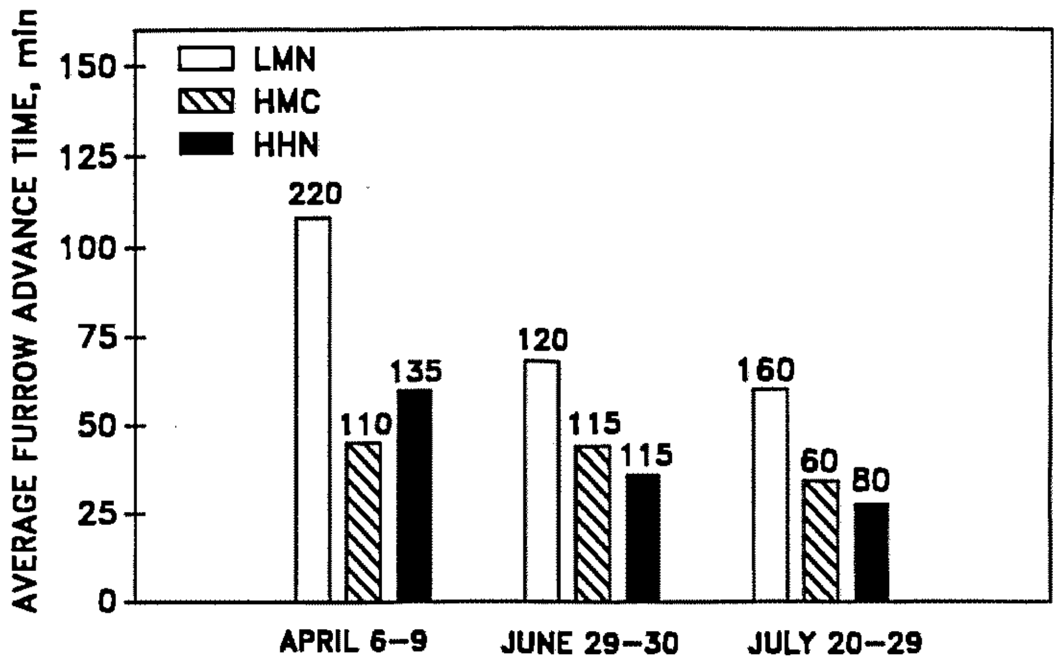

Figure 1. 1993 level basin furrow advance comparison for preplant, mid-season, and late-season irrigations of cotton by the low-frequency, non-compacted (LMN); high-frequency, compacted (HMC); and high-frequency, higher basin inflow rate, non-compacted (HHN) treatments. Gross application depth in mm is shown above each treatment bar in the figure.

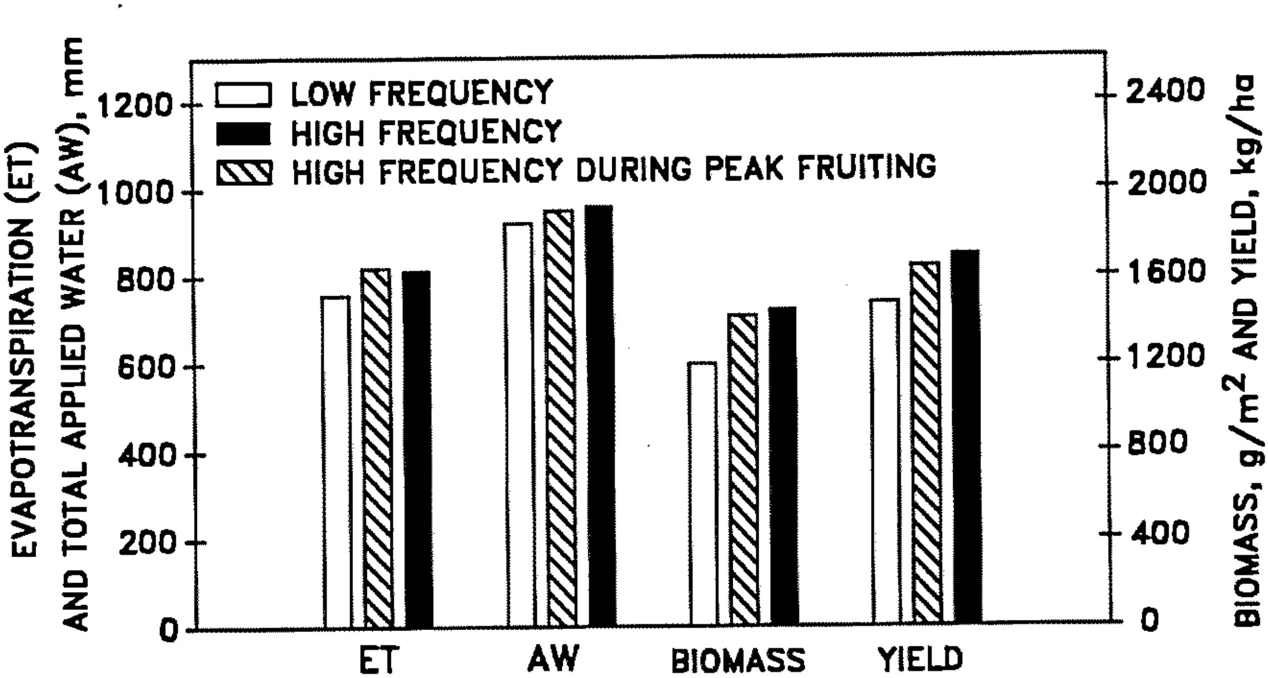

Figure 2. Evapotranspiration, total water applied, aboveground biomass, and lint yield for three irrigation frequencies in the 1993 small plot cotton study.

MODIFIED LEAF GATES FOR CANAL CONTROL AND FLOW MEASUREMENT

B.T. Wahlin, Civil Engineer; and J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Leaf gates, sometimes called overshot gates, are being used in the Imperial Irrigation District (IID) and in many other places such as floodways from the Salt River Project (SRP) canals. These gates are built by a company in Fresno, California. Their general configuration is shown in Figure 1. Advantages of these gates include the ability to obstruct or control flow from essentially no interference to complete shut-off. A disadvantage is the high forces required to raise the gate. Another disadvantage is the side seals which limit the gate's practical application to rectangular channel sections.

The gate is widely used in the control mode when water level is the desired criterion. However, often both flow control and measurement are desired. In this capacity, the leaf gate would be monitored for depth of flow over its crest, and this value would be used to determine the discharge. The control aspect of the gate would imply that the water source is a lake or a canal capable of responding to control of the backwater effects that would be required to discharge a fixed flow rate. This use of the leaf gate as a flow measuring weir with a variable sloping front face appears to be valid if properly determined coefficients can be verified for use in the sharp-crested weir equation of the form

$$Q = C_e b \sqrt{2g}\, h^{1.5}$$

in which C_e = effective discharge coefficient; b = width of the weir; g = gravitational constant; and h = the measured head of the water approaching the gate.

For depth control purposes only, ventilation of the crest is not required. However, if the overshot gate is to behave as a freefall measuring weir, the crest must be properly ventilated. This criterion strictly limits the depth of water in the downstream channel because the downstream water must be about 5 cm below the overspill crest to assure proper ventilation. Because these control gates are operated regularly under submerged conditions, it also is desirable to investigate the submergence characteristics of the gates. Although sharp-crested weirs are not normally designed to operate under drowned conditions because their accuracy is greatly reduced, the flow rate still can be determined by using a modified sharp-crested weir equation in the form

$$Q = C_{df} Q_o$$

in which Q_o = discharge under freefall conditions and C_{df} = drowned flow reduction factor. If the overshot gate behaves similarly to a vertical sharp-crested weir under submerged conditions, then the gate could be used as a flow measurement device regardless of the downstream water depth.

APPROACH: A commercial version of the overshot gate was obtained from UMA Engineering and Armtec, Inc. The leaf gate is constructed of stainless steel 3 mm thick. The length of the gate is 50 cm, and the width is 114 cm. The entire overshot gate was fitted into a glass-lined laboratory channel 123 cm wide and 60 cm deep. The hoisting mechanism used to raise and lower the gate limited the maximum angle that could be achieved to about 55°.

Two different tests were performed on the overshot gate. First, the gate was calibrated under freefall conditions for gate angles varying from 15° to 51°. A discharge coefficient was determined at each gate angle that would allow the sharp-crested weir equation to be used to predict discharge. Next, the overshot gate was calibrated under a variety of submergence conditions. From these data, the drowned flow reduction factor was determined as a function of the submergence ratio and gate angle. Finally, these two tests were repeated at different widths of the overshot gate. In this way, any contraction effects on the calibration of the gate could be determined.

All flow rates were determined with the laboratory weigh tank system, which is accurate to ±0.1%. The hinge joint on the overshot gate leaked only slightly, and it was assumed that these small leaks did not affect the calibration of the gate.

FINDINGS: Under free fall conditions, it was assumed that the effective discharge coefficient was of the following form:

$$C_e = C_d C_a$$

where C_d = effective discharge coefficient for a vertical sharp-crested weir and C_a = correction factor based on gate angle. Figure 2 shows the angle discharge coefficient as a function of h/p (p = height of leaf gate overfall edge from channel bottom) for various gate angles and side contractions. It can be seen that the angle discharge coefficient remains virtually constant over the flow range tested and varies due only to the gate angle and the side contraction. As the angle and contraction increase, the angle discharge coefficient also increases.

A plot of the drowned flow reduction factor versus submergence ratio appears in Figure 3. It can be seen from this plot that the drowned flow reduction factor has a shape similar in appearance to that of vertical sharp-crested weirs. Also, the drowned flow reduction factor approaches the values of a vertical sharp-crested weir as the leaf gate angle is increased. The drowned flow reduction factor can be expressed by a modified Mavis equation as follows:

$$C_{df} = 1 - nS^{1.5} - \frac{m}{2^{(10-10S^{1.5})}}$$

where S = submergence ratio (h_2/h_1) and n and m = empirical constants. In the Mavis equation, n = 0.45 and m = 0.40 for a vertical weir.

INTERPRETATION: It should be expected that as the angle on the leaf gate is increased, its hydraulic behavior should become more similar to that of a vertical weir. In this case, the value of C_a should approach 1.0 as the leaf gate approaches vertical. However, it can be seen in Figure 2 that this is not the case and that C_a actually increases as the angle of the gate increases. This can be explained by observing that the slope of C_e for the leaf gate is flatter than the slope for C_d in the vertical weir equation. The difference between the two slopes of the calibration curves may be due to the straightening out of the streamlines as the water flows over the inclined plate of the leaf gate. A reduction in the h/p value, which corresponds to an increase in the gate angle, will cause an increase in the difference between these two lines and in the value of C_a because the slopes of the C_d and C_e lines are different.

The submerged characteristics of the gate are similar to those of a vertical weir. As the gate angle is increased, the drowned flow reduction factor approaches the values given by the Mavis equation (see Fig. 3). This trend agrees with what is to be expected as the gate approaches vertical.

Side contraction does not appear to affect the submergence characteristics of the overshot gate. Contraction ratios of around 0.80 and 0.50 were used on some tests, and no differences could be detected in the gate's submergence characteristics. However, the side contraction does affect C_a. As the side contraction of the overshot gate is increased, the value of C_a is also increased.

FUTURE PLANS: Field calibrations of an overshot gate in IID have already been performed. The data will be analyzed to determine if the field calibrations of the overshot gate are hydraulically similar to those performed in the lab. Recommendations on the effectiveness of the overshot gate as a flow measurement device as well as its limitations will be determined. Possible modifications of the leaf gate to improve its flow measuring capabilities also may be examined.

COOPERATORS: UMA Engineering, Imperial Irrigation District, and Armtec, Inc.

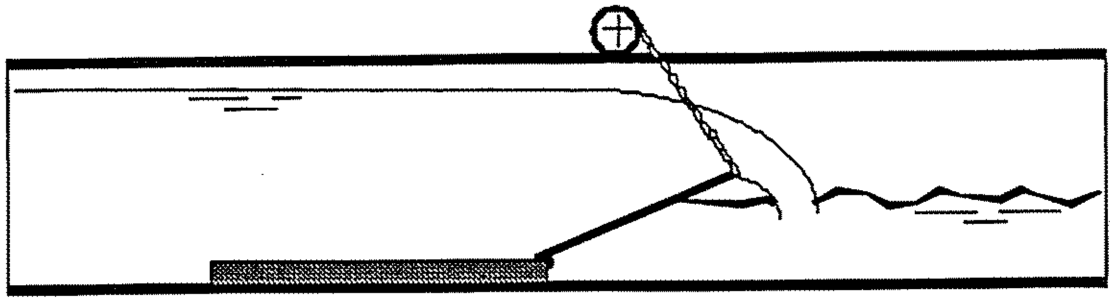

Figure 1. General schematic of a leaf gate.

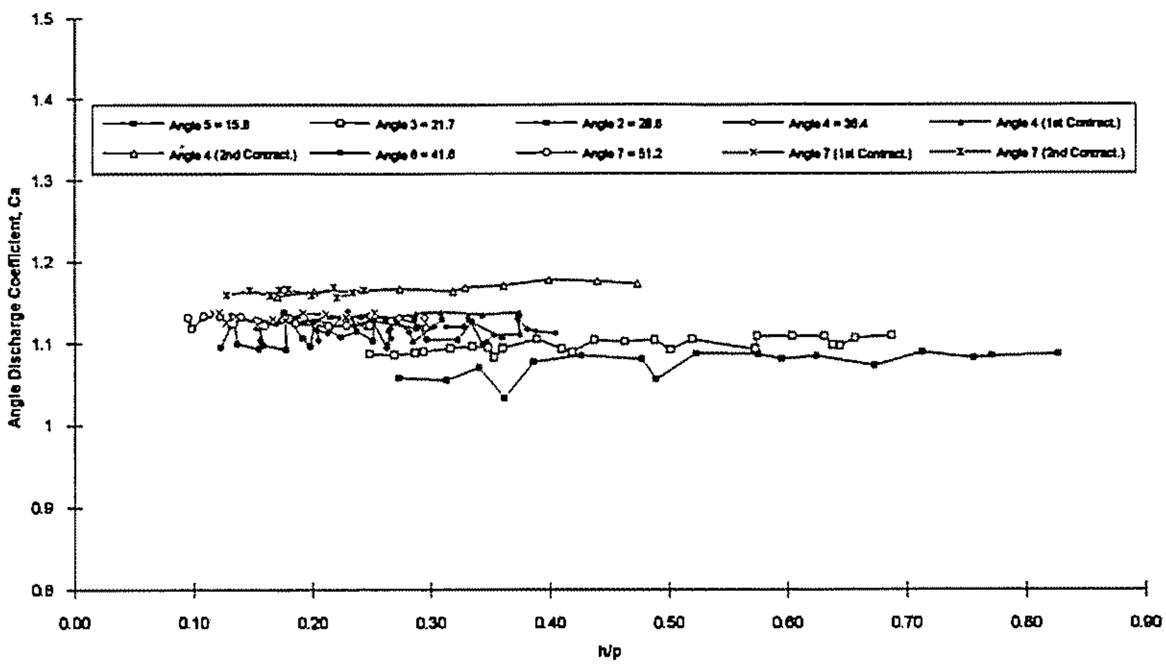

Figure 2. C_a as a function h/p.

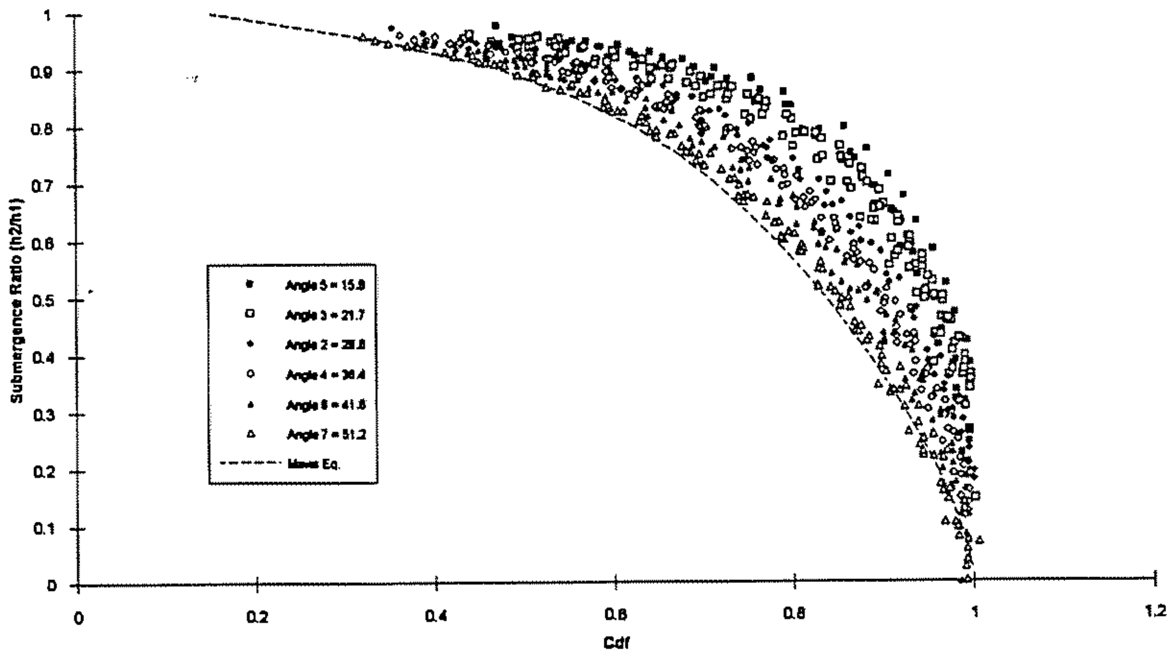

Figure 3. C_{df} characteristics of leaf gate.

SOFTWARE FOR DESIGN AND CALIBRATION OF LONG-THROATED MEASURING FLUMES

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Flow measurement in irrigated agriculture continues to be a difficult problem. Flow measurements are frequently inaccurate, and structures are often improperly installed. Over the last decade, the long-throated flume has been developed as a very useful tool for improving water measurement in irrigation canals. One of the advantages of this device is that it can be custom designed for each installation, thus better meeting the needs of the measurement site. This can be a disadvantage in that it gives the user so much flexibility that an optimum structure may not be selected.

A computer program, FLUME, has been available since 1987 for the calibration of these flumes. It is not very user friendly; users frequently make errors in data input; and laboratory personnel spend a significant amount of time answering user questions. Thus, there is a need for a more user friendly flume program that can aid the user in design of these flumes.

APPROACH: A menu-driven program, FLUME3.0, has been developed to aid in the design and calibration of long-throated flumes for irrigation canals and natural channels. The program includes design procedures developed over the last few years. The user inputs the conditions of the canal and selects the type of contraction desired. Then the program suggests a structure that meets the channel conditions. The program also has graphic data input that shows the flume profile and cross sections so that when the user enters flume dimensions, the changes can be viewed immediately. This should greatly reduce the chance of user error. A database of flume designs and calibration tables also is provided. The project is being sponsored by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. A software programmer from Wageningen is under contract to ILRI to write and maintain the program.

FINDINGS: The program and users' manual have been completed and released for sale by ILRI. Several bugs were found in the earliest release and these now have been fixed. ILRI has been receiving about 30 orders per week since the program has been available. It will also be marketed through Water Resources Publications in Fort Collins, Colorado.

INTERPRETATION: This program should help the transfer of this technology to users in a very effective manner. It will make these flumes an even more valuable tool for improving water management in irrigated agriculture.

FUTURE PLANS: Maintenance on the computer program will be the main activity during 1994. Depending on the rate of sale and number of users, we will begin upgrading the program to add features.

COOPERATORS: M.G. Bos, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands; and J.M. Groenestein, Groenestein and Borst Ltd.

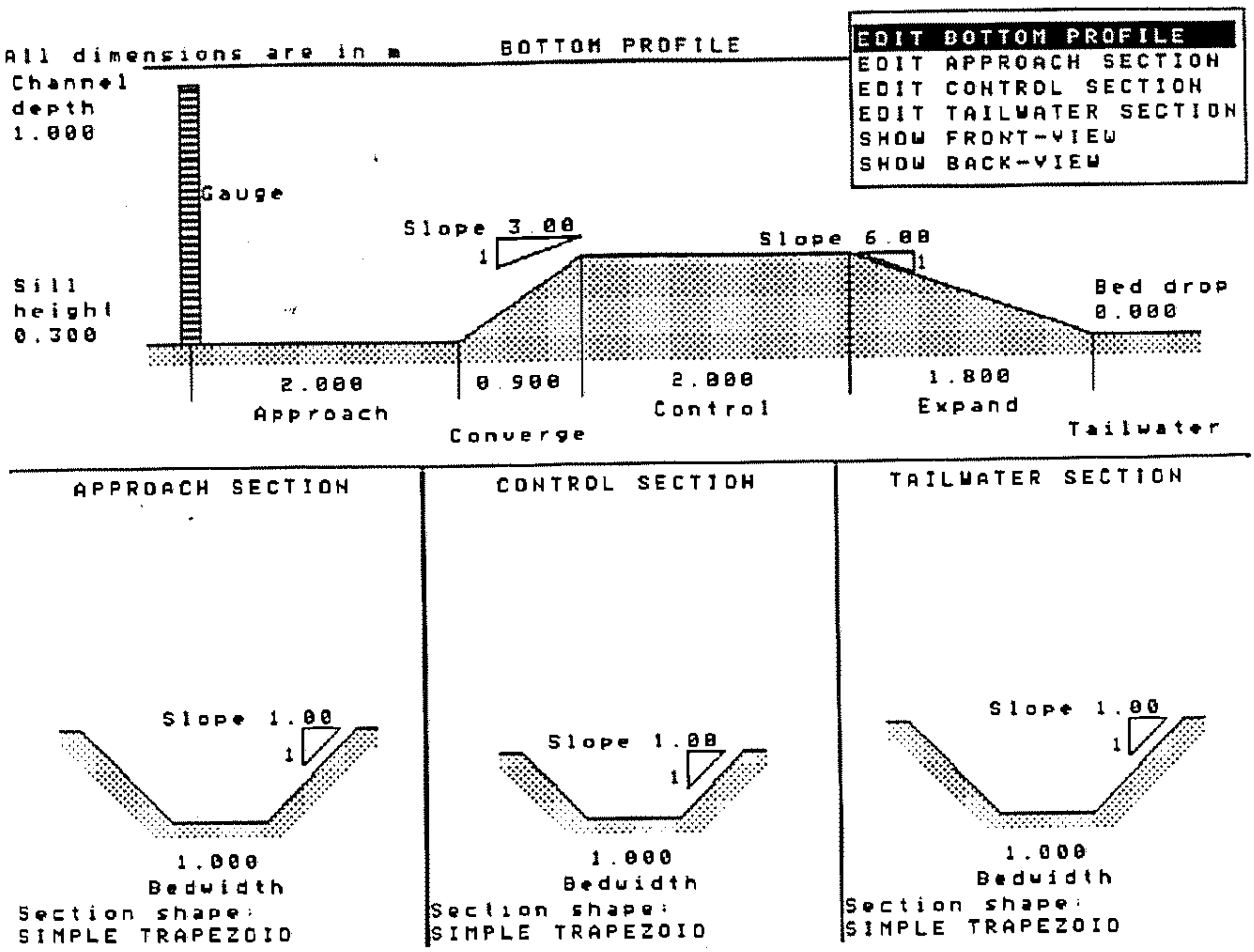

Figure 1. Graphics data entry screen for default flume

```
User : Clemmens/Bos/Replogle            Report made on: November 20, 1992
Flume: Phoenix , example structure used in manual                Version  3
                       EVALUATION OF FLUME DESIGN

GENERAL RESULT : Design is acceptable.     2 lines of error/warning text.
                Headloss design aims are not fully met

              EVALUATION OF FLUME DESIGN FOR EACH DESIGN CRITERION

Ok.    Freeboard at Qmax.:    Actual=0.356 m    Minimum=0.094 m

Ok.    Head at Qmax.:         Actual=0.469 m    Minimum for accuracy=0.235 m

Ok.    Head at Qmin.:         Actual=0.100 m    Minimum for accuracy=0.099 m

Ok.    Tailwaterdepth Qmax.:  Actual=0.844 m    Maximum allowed=0.858 m

Ok.    Tailwaterdepth Qmin.:  Actual=0.109 m    Maximum allowed=0.507 m

Ok.    Froude nr. at Qmax.:   Actual=0.315      Maximum= 0.500

                    ADVICE, WARNINGS AND ERROR MESSAGES

Headloss design aims are not met.
Too much contraction in initial control section shape

                          RESULTING STRUCTURE.

Sill Height = 0.425 m
CONTROL SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bedwidth = 1.850 m              Channel side slope =  1.00:1

                           DESIGN STRATEGY.

Headloss design aim: Minimize headloss
Contraction change strategy: Vary height of sill

                           DESIGN CRITERIA.

Type of structure: Stationary crest.
Freeboard design criterion: Percentage of head over sill = 20 %
Allowable discharge measurement errors for a single measurement:
  At minimum discharge:  8.00 %.    At maximum discharge:  4.00 %
Head detection method: Staff in still Fr=0.2  Readout precision: 0.005000 m
Design discharges and associated tailwater levels:
  Minimum discharge=  0.100 m3/s    Minimum tailwater level=  0.109 m
  Maximum discharge=  1.300 m3/s    Maximum tailwater level=  0.844 m
  Values derived using: 2 Q-H measurements
== Use cursor keys, PgUp, PgDn, etc. to view whole text==================
```

Figure 2. FLUME design results screen.

IRRIGATION CANAL HYDRAULICS AND CONTROLS

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Surface-irrigation efficiency most easily can achieve high levels when the supply canals have been designed and are operated in a way to supply the necessary water at the right time to each of the users of the resource. In present systems, the possibility of meeting the canal-delivery requirements for efficient demand irrigation is not assured. The operation of gates and pumps in a canal system produces waves, which transmit the effects of these operations throughout the system at a speed not much in excess of water velocity. The total effect at any location is the combined result of these waves, transformed during their travel, that arrive there from their points of origin. Numerical simulation of the unsteady flow encountered in irrigation canals allows prediction of the results of given physical designs and management procedures.

As irrigation canal systems become more responsive to farm demands, changes in flow occur more frequently, causing unsteady flow throughout the system. Even large canal systems with rigid delivery policies that supposedly operate under steady flow often have unsteady flow for long periods of time. Most canal systems operate with manual upstream control. Here a constant water level at an offtake is used to keep delivery flow rates constant. The disadvantage of this system is that all flow management errors end up at the tail end of the system. In large canals, supervisory control systems are used to adjust volumes in intermediate pools to keep differences between inflow and outflow more evenly distributed in the system or simply stored until a balance is achieved. Smaller canals with insufficient storage need more precise downstream control methods than are currently available.

Many computer models of unsteady canal flow have been built in the last twenty years; some very complex and expensive, designed to model very complicated systems. Proprietary code is not readily accessed for modification to reflect new operating conditions or for incorporation into optimization routines. Some models, adopted by agencies and associated with years of experience, are reliable except when, physically, a hydraulic bore forms. Approximate means are presently available for judging bore formation but are not in common use; use of an unsuitable model for simulation of these cases leads to incorrect results, not necessarily identifiable.

The objective of this research is to develop tools for the improved operation of irrigation canal networks, more specifically to improve canal control algorithms, improve predictive capabilities of unsteady flow simulation programs, improve manual operating techniques, and improve local automatic gate controllers.

APPROACH: Advances in control engineering have not been applied fully to irrigation canal downstream control. A few downstream control techniques are in use, but they have not been fully tested to determine their limitations. To aid in the evaluation of existing techniques and development of new ones, data will be collected on a few canals that may be difficult to control with existing methods. Further, we will collaborate with canal control experts to assess various methods for automatic feedback control and assist in the implementation of these methods on these test canals. Canals within the Maricopa Stanfield Irrigation and Drainage District (MSIDD) will be studied because they have the hardware to control gates automatically at all check structures within lateral canals. The first step in this research program will be to test these algorithms with an unsteady-flow simulation model.

The performance of automatic feedback canal control algorithms is influenced by the general properties of the canal, the nature of demand changes (and how well they are known ahead of time), and the properties of the control algorithm (and how well it is adapted to the canal). Nondimensional expression of criteria is expected to allow a more general application. Feedforward canal control algorithms are influenced by level of knowledge of specific canal parameters and the amount of unanticipated disturbances. The approach taken here will be to combine these two aspects of control in order utilize the advantages of each where possible.

The general approach is to find the simplest controller that will be suitable for a particular canal.

FINDINGS: A canal control example was developed based on the field data collected during 1992 on MSIDD's WM canal. The objective of the controller for this example is to adjust canal inflow and check gates to provide a constant water level upstream from each gate, which implies a constant discharge to farm offtakes. The example canal was tested by Jan Schuurmans with unsteady simulation (program MODIS) of his PI and PI+Decouplers feedback controllers, which adjust each gate according to the error in water level in the next pool downstream. It was shown that for this canal, feedback control without anticipation of scheduled flow changes would be unsatisfactory. Further testing was conducted through simulation with CANALCAD on several other simple PI controllers to determine their characteristics and to examine the possibility of combining feedback with feedforward control.

With feedback control only (no anticipation), simple PI controllers (including CARDD) performed poorly. Better control was found when decouplers were used to remove the influence of changes in one gate from gate actions upstream and downstream. The Decoupler I transmits needed downstream changes to upstream gates, thereby improving speed of response. The Decoupler II adjusts gates downstream to counter the influence of upstream gate changes. Decoupler II effectively requires some form of knowledge about canal response (e.g., a model of transient waves).

It was found that PI controllers based on flow rate eliminate the need for Decoupler II, since a change in upstream level csuses the gate opening to change to maintain a constant flow rate. Thus, some knowledge of gate hydraulics replaced the need to include a model of canal response in the controller.

Initial computer simulation tests on combining feedforward and feedback control were encouraging. We anticipated conflicts between the feedforward and feedback controls. These conflicts were evident during control of a single canal reach but were, not significant for multiple reaches. Adding feedforward improved control significantly even when feedforward timing was not ideal.

Work has begun, in conjunction with an ASCE task committee, on determining methods for quantifying canal properties that suggest their suitability for various automation methods.

Testing of optimal control with CANALCAD on the MSIDD Santa Rosa canal also was initiated during 1993.

INTERPRETATION: Unsteady flow models are a useful tool for evaluating canal operations and control algorithms. Simple feedforward-feedback Pl controllers appear to be feasible even for difficult canal control situations.

FUTURE PLANS: Additional testing will be done with simple PI controllers on the MSIDD WM canal to determine their suitability for field testing. The PIR controller developed by Deltour at GERSAR in France needs to be tested to determine whether adding a Smith controller (canal-response predictor like decoupler II) is of benefit. Then software to implement these controllers at MSIDD will be written. Some hardware modifications to existing field gate controllers will be made, followed by initial testing of these simple algorithms on the actual canal.

COOPERATORS: Gary Sloan, MSIDD; Pascal Kosuth, CEMAGREF; Charles Burt, Cal Poly; Wytze Schuurmans, Delft Hydraulics; Jan Schuurmans, Delft U. of Technology; John Parrish, Utah State U.; Mohan Reddy, U. of Wyoming;

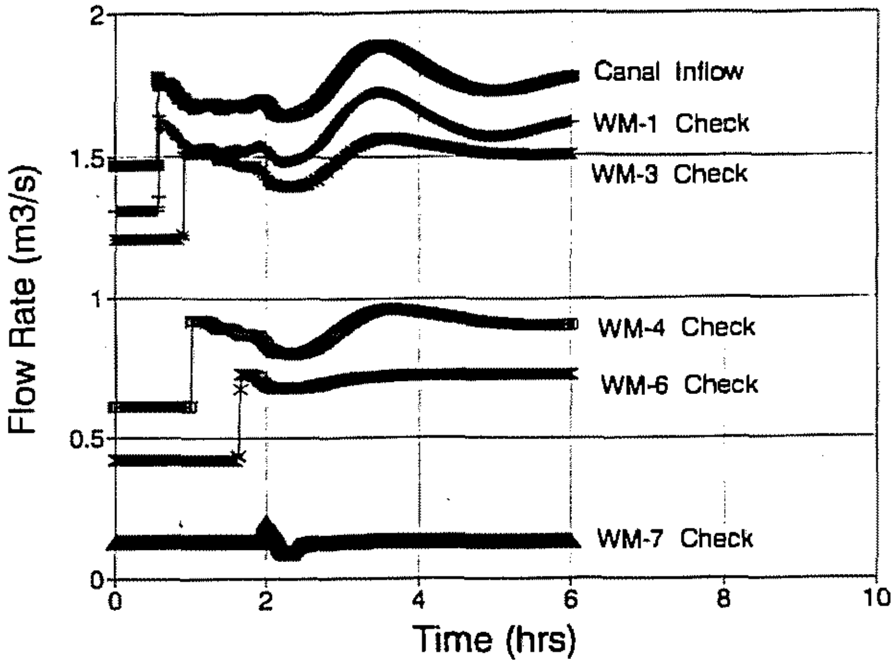

Figure 1. Canal WM: Simulated flow rates through check gates calculated from simulation for a step change in outflow at pool 7 at 2 hours. Combined feedforward-feedback control based on flow rate with decoupler I. (Improper tuning of decoupler I caused the oscillations after 2 hours.)

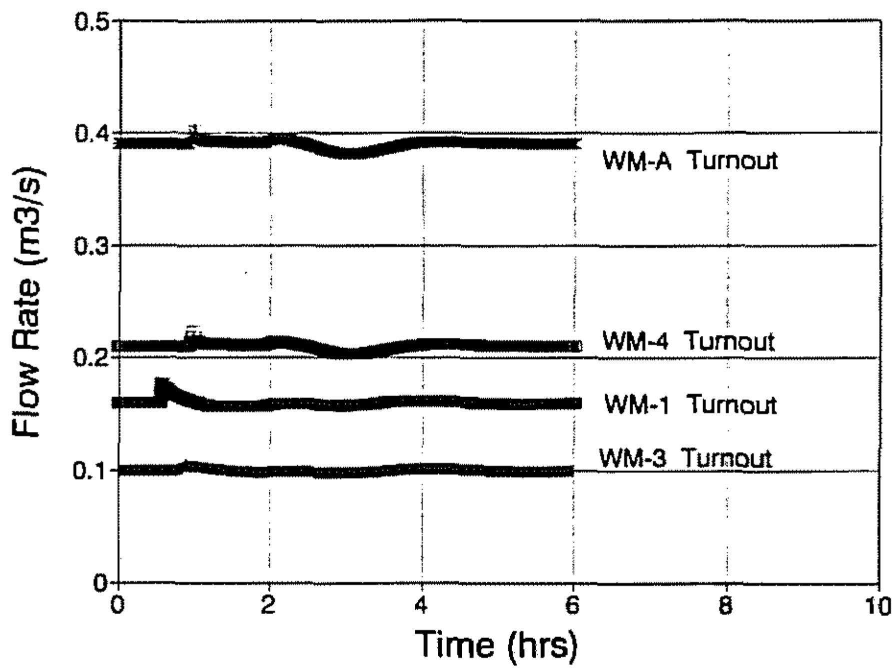

Figure 2. Canal WM: Simulated flow rates through offtake gates (pools 1-4) calculated from simulation for a step change in outflow at pool 7 at 2 hours. Combined feedforward-feedback control based on flow rate with decoupler I.

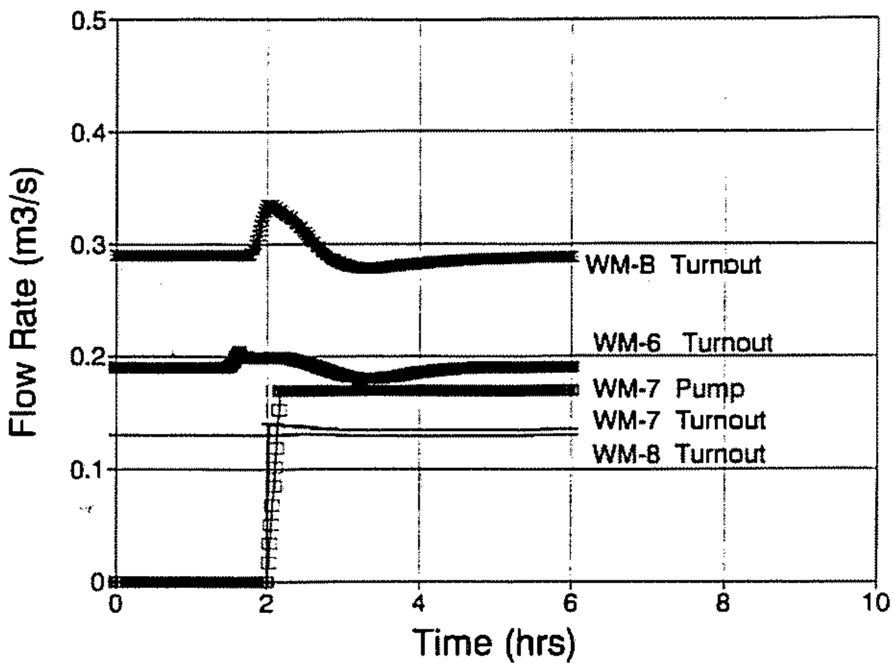

Figure 3. Canal WM: Simulated flow rates through offtake gates (pools 5-8) calculated from simulation for a step change in outflow at pool 7 at 2 hours. Combined feedforward-feedback control based on flow rate with decoupler I. (Error in turnout WM-B flows was due to error in feedforward timing.)

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and locally in excessive amounts, leading to wastage and to pollution of ground and surface waters receiving the excess. The interaction of the many variables significantly influencing the movement of irrigation streams down fields, and, ultimately, the distribution of infiltrated water and the amount of runoff from the irrigation, is too complicated for simple calculation. A mathematical model--a numerical, computer solution of the pertinent governing equations--supplied with the conditions of the irrigation can, on the other hand, allow rapid determination of the consequences of a given physical design and management procedure. Systematic, repeated simulations allow determination of design parameters to yield optimum uniformity of infiltrated water and minimum runoff from the end of the field, as reported under a separate research project. This, in turn, can reduce the degradation of groundwater supplies by excess irrigation water, contaminated by fertilizers and pesticides, percolating below the root zone of the crop. Similarly, reduction and reuse of field runoff protect surface-water supplies downstream from irrigated fields.

Current models of surface irrigation require further development to extend the range of conditions they are designed to simulate and to increase the reliability of their mathematical procedures. New irrigation techniques generally precede attempts at simulation, so models must be revised to allow theoretical study of the innovations. Furthermore, present models do not always complete a simulation. A physical condition that can arise with cut-back flows is a temporary retreat of the leading front of the stream, eventually halted and once again moving forward. The present model simulates this motion only crudely. In addition, certain flow conditions--notably, very slow advance on the order of a foot per minute with potential, incipient front-end recession--present poorly posed problems both physically and mathematically. A potential computer response is the generation of a negative depth with consequent premature front-end recession.

The present treatment of surges overtaking previous releases is not realistic and needs improvement. Likewise, overflow into a drainage ditch through critical depth, as currently postulated, is not a realistic representation of current farm management; typically, the drainage ditch is given a sufficient depth of water to prevent the erosion that would occur if critical conditions were, in fact, present at furrow end.

All of these physical circumstances are likely to occur in the investigation of practices leading to efficient irrigation; the inability to simulate these properly hampers the search for an optimum design.

The current ARS surface-irrigation model, in spite of improvements in format, still requires data entry more complicated than many potential users are willing to negotiate.

APPROACH: Restructuring of current programming and additional programming to simplify code and extend the scope of application of the model is underway. The equations governing the flow of water in the surface stream are known, and computer algorithms for solving these are generally straightforward. An exception is the case of non-monotonic stream advance as a reasonable assumption regarding the effect of rewetting upon infiltration will have to be implemented. The current approach follows Smerdon and Blair utilizing pieces of the infiltration-time curve corresponding to wetted periods. The current approach to very slow flow is simply to allow it to advance and retreat as the numerical approximations to the flow equations dictate.

FINDINGS: An experimental version, SRFR 20.8, of a user-friendly menu-driven surface-irrigation model is approaching completion and distribution to cooperating researchers. The program consists of three large segments, each approaching the DOS 640k ceiling in size, interconnected through small batch files. The segments comprise a menu-driven data-input front end which generates a data file; an engine, which performs the simulations specified in the data file; and a menu-driven back end which allows for viewing the graphical results of any group of simulations. The use of exit codes to enable calls to any particular segment from any other segment makes the interfaces between the segments transparent to the user. The front-end program was originally written in Borland C++; for greater compatibility and eventual linkage with the FORTRAN engine, the front end is being rewritten in ZINC C++. The back end is in ZINC.

In a departure from previous simulation data entry, the time parameter in the inflow management scheme is now allowed, at user discretion, to be set by stream behavior. In particular, the Wattenburger and Clyma completion-of-advance design recommendation sets cutoff when the stream reaches field end in a level basin. The SCS furrow-irrigation design recommendation—cutback when the stream reaches field end and cutoff when the required depth of infiltration has been met at the downstream end of the field—can also be implemented.

The heart of the engine has been restructured and essentially rewritten with debugging currently underway. Front-end recession occurring despite continuing inflow at the head end of the field is simulated by contracting the stream to that portion with only calculated positive depths, redistributing computational nodes within, and allowing advance to continue when the inflow is capable of satisfying the infiltration requirements of the stream length.

Work is continuing on simulating the advance of small streams over highly irregular terrain. The sharp changes in stream profile shape and speed of advance as the stream crawls up a local incline and plunges down the other side tax the ability of the model to solve the nonlinear governing equations.

INTERPRETATION: To make a significant impact on surface-irrigation design and practice, computer models of the process must be of broad scope, fast, and reliable, yielding simulations for every reasonable combination of circumstances, and with convenient, user-friendly data input and graphical display of the results of any given set of design and management parameters. This is the aim of current development.

The simulation model is capable of providing quick results for various test combinations of design and management parameters, thus allowing these to be optimized.

FUTURE PLANS: Current deficiencies in model behavior as outlined above will be addressed. Given the large size of the model and the memory limitations of most computers in the field, flexibility in distributing that memory to the greatest benefit of the user also will be addressed. The latest versions of compilers and linkers will be investigated.

COOPERATORS: D. D. Fangmeier, The University of Arizona, Tucson, AZ; J. Cahoon, University of Nebraska, Lincoln, NE; K. Admire, SCS, Dexter, MO; M. English, Oregon State University, Corvallis, OR.

REFERENCES:

Wattenburger, Paul L. and Clyma, Wayne (1989) "Level basin design and management in the absence of water control, Parts I and II," Transactions ASAE, Vol. 32, No. 3, May-June. pp. 838-850.

USDA, Soil Conservation Service (1984), National Engineering Handbook, Section 15, Chapter 5 (Second Edition), Furrow Irrigation. pp. 1-96.

SURFACE IRRIGATION SYSTEM EVALUATION, DESIGN, AND MANAGEMENT

A.J. Clemmens, Supervisory Research Hydraulic Engineer;
T.S. Strelkoff, Research Hydraulic Engineer; and A.R. Dedrick, Supervisory Agricultural Engineer

PROBLEM: Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, you supply the actual conditions, and the model determines the results of the irrigation. Design represents the opposite situation; for a desired irrigation result or output, the designer wants to know how to specify inputs: field dimensions and operating procedures. This is complicated by infiltration and roughness conditions which change over the season and are generally not known. Most existing design procedures specify recommended field dimensions but rarely recommend operating procedures. Thus, even a good design may result in poor performance unless the operator is given appropriate *operational guidelines*. In many cases, design is based on procedures or equations that have only a limited range of usefulness. It is generally difficult for the designer to know how a surface irrigation system will perform until it is laid out and irrigations commence. Analysis based on computer simulation of unsteady flow has been the most reliable design tool but currently is complicated to use.

One of the difficulties in applying computer simulation models is the lack of information by the designer on parameters that define field conditions, particularly infiltration and roughness. Existing irrigation evaluation techniques can be used to define some of these parameters. And while a number of evaluation techniques are available, different techniques are appropriate under different conditions. Little analysis has been done on the range of usefulness of the various methods and in defining how much data is really necessary for an effective determination of field parameters. For example, several research studies have shown that a constant Manning roughness value for vegetative borders may not be appropriate. Other expressions have been proposed.

The objective of this project is to develop user friendly software for the evaluation, design, and management of surface irrigation systems that is usable in a variety of surface irrigation settings.

APPROACH: Reliable predictive models are the first step in the development of surface irrigation software. Model development is discussed under a separate research project. There are two approaches to developing design results from simulation: (1) to look up results already generated from a simulation model, or (2) to search for an acceptable (or optimal) design solution by iterating with the simulation model. With current computing machines, the former is still preferred; however, as increasingly faster machines become available, the latter provides more latitude in design objectives and field conditions.

Generalized design and management guidelines have yet to be developed from the models. These guidelines can be in the form of tabulated results, regression equations, or procedures for systematically applying the predictive models. This step is necessary for practical application of predictive models. Several approaches will be taken in the development of these design guidelines. They include the development of: (1) nondimensional solutions for general problems (e.g., optimal design) that can be computer coded, (2) search procedures for more specific problems (i.e., a series of simulations with inputs that are varied to achieve the desired outcome), (3) design procedures that take into account the changes in field parameters that occur over the season, and (4) sensitivity analysis of design input.

Generalized design results for level basins were developed previously based on SCS design procedures. However, Wattenburger and Clyma developed design solutions based on cutoff at the end of advance, which may be more applicable for level basin design where flow rates are unreliable. Field experience indicates that most irrigators use a spot in the field to determine when to cut off the stream (i.e., something less than the end of the field). This suggests that design (and thus any design procedures or solutions proposed) should consider the operator's cutoff criteria.

In addition, one must be able to include other factors which affect uniformity and efficiency; namely, soil spatial variability, surface irregularities, and nonuniform inflow streams. Various studies will be conducted to assess the impact of these conditions. Procedures will then be developed to account for these factors in the design and operating procedures.

One limitation of existing programs is that the user must be able to quantify field conditions for infiltration and roughness. There is a need for a general program on field evaluation procedures to assist users in determining field conditions and parameters for input into these design and operation programs.

Efficient and robust search procedures need to be developed for finding optimal designs. Most search procedures are not totally reliable when applied to surface irrigation modeling.

FINDINGS: The nondimensional design results for level basins were previously coded into a menu-driven design program. This program, BASIN, was intended only to replace the SCS design charts. The entire set of non-dimensional results were rerun with BRDRFLW so that additional information could be provided on advance distance at cutoff, advance time and water depth. New procedures were developed to include design based on *advance distance at cutoff*. These new routines have been added to BASIN.

Initial design curves for low-gradient sloping borders have been developed. Further analysis and development are needed to make these into useful design solutions.

An overview of the literature on the use of dimensional analysis in surface irrigation was completed and submitted for review. This document provides the framework for future research and development in this area.

Preliminary analysis of Merriam's advance-ratio concept has been performed. Additional analysis is needed to determine its range of applicability.

INTERPRETATION: While significant advancements have been made on the development of predictive models, significant impact will occur when these models can be incorporated into some form of user-friendly software. Only in this way will these models impact water use efficiency in irrigated agriculture. This must be done in the context of grower management practices.

FUTURE PLANS: The BASIN program, including a short users' manual, will be completed and released during 1994. Also in 1994, work will start on adding the influence of land-leveling precision on the distribution uniformity to BASIN.

The new project to develop design solutions for low-gradient, blocked end borders with the University of Arizona will continue. These are a logical extension of the solutions for level basins.

Current SCS design procedures for sloping furrows will be reviewed in the light of results from computer simulation of furrow flow. Cooperative work with the University of Arizona on level furrow design also has begun.

Further analysis of simple evaluation procedures will be conducted. Also, relationships for expressing vegetative resistance in cropped basins and borders will be examined.

Long-range plans are to develop a general software package for surface irrigation systems along the lines of BASIN but expanded to include sloping borders and furrows and to include the actual simulation model as well as generated design results and evaluations. The University of Michigan has developed search procedures for surface irrigation parameter estimation. We will examine these procedures to determine their suitability for use in design.

COOPERATORS: N.D. Katopodes, University of Michigan, Ann Arbor, MI; D.D. Fangmeier, The University of Arizona, Tucson, AZ; T.A. McMahon, University of Melbourne, Melbourne, Australia; W. Clyma, Colorado State University, Fort Collins, CO.

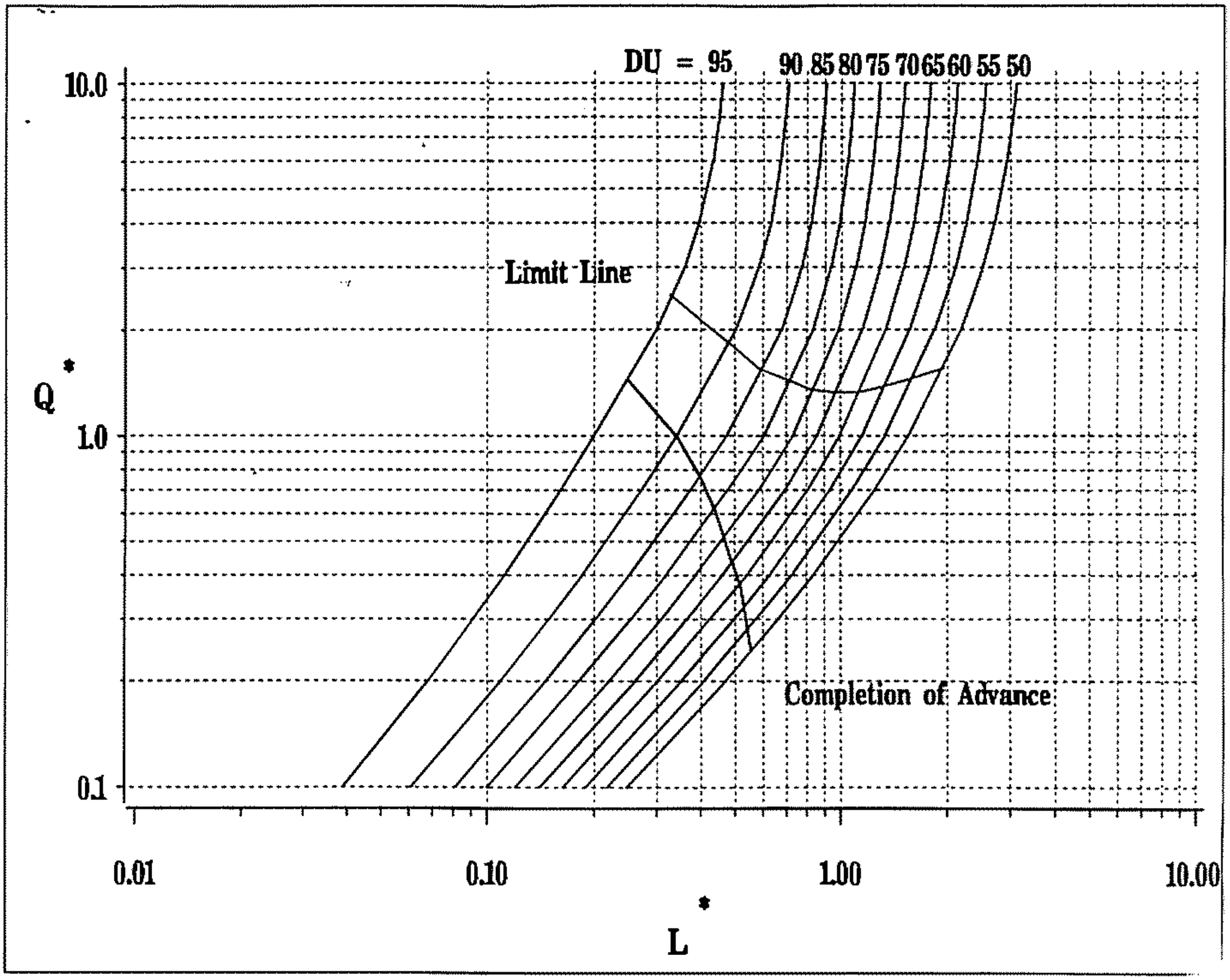

Figure 1. Level basin design charts showing the completion of advance design.

MODELING THE INFLUENCE OF LAND LEVELING PRECISION ON SURFACE IRRIGATION PERFORMANCE

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Surface irrigation systems inherently distribute water non uniformly over the land area to be irrigated. This non-uniform distribution of water can cause a number of problems. First, areas receiving too little water can experience crop stress, yield reductions, and salinization from insufficient downward movement of water. Those areas receiving too much water can leach fertilizers and contribute to rising water tables, again leading to salinization. Farmers tend to over irrigate so that they do not get crop water stress from under irrigation. However, this leads to excess deep percolation and rising water tables on adjacent lands. These problems are much more acute on reclaimed lands. Poor irrigation uniformities increase tbe amount of time needed to bring reclaimed land into full production.

One of the main contributors to surface irrigation uniformity is the precision of land leveling. Greater precision is needed as land slopes get flatter, with level basins requiring a high degree of land leveling precision in order to obtain reasonable uniformities. Experiences in the US indicate significant improvements in irrigation uniformity and efficiency with improvements in leveling precision on level basins. While some information on leveling precision and its influence on production in Egypt is available, the degree to which leveling precision in Egypt affects crop production and water management in not fully known.

Mathematical models of the advance and recession of water over a surface-irrigated field are useful tools for predicting irrigation uniformity and efficiency. However, current models can handle only major undulations in the field surface, and only in one dimension. They cannot model fully the two-dimensional nature of water flow in basins or multiple furrows.

APPROACH: These existing surface irrigation models will be used in this study to take a first look at the effects of surface irregularities on uniformity. Part of this project will be to extend the existing irrigation models to multiple furrows and/or two dimensions so that they can handle more adequately real field conditions. Field data will be collected to determine existing conditions in Egypt and for verifying the models developed. Existing land leveling and tillage practices will be evaluated to determine their influence on the leveling nonuniformity. Finally, assessments will be made regarding the magnitude of the impact of poor land leveling in Egypt; and design and management guidelines will be developed to aid in making decisions for improvement in surface irrigation practices, including recommendations on leveling and tillage practices. This ultimately is expected to improve the effectiveness of water use in irrigated agriculture, both in Egypt and the US.

FINDINGS: Initial data have been collected in Egypt to define the amount of non uniformity in field surface elevations that exists under conventional-leveling and laser-leveling practices. A new version of the SRFR surface irrigation program is nearly completed and will be used for the initial analysis of leveling precision. The BASIN irrigation design program also has been revised to include design based on operating criteria. This program will be used to develop recommendations for design and operating criteria that take into account the effects of leveling precision.

Several two-dimensional models of surface irrigation flow have been examined. The simpler methods will not accommodate an irregular bottom and are thus not useful for this study. Several other models are under development and are not yet capable of modeling the conditions under typical level basins.

Plans have been developed for field data collection in Egypt and include an assessment of irrigation performance as influenced by leveling uniformity.

Training of Egyptian scientists has focused on irrigation hydraulics and modeling, flow measurement, field data collection procedures, and general mathematics and irrigation engineering.

INTERPRETATION: It is expected that leveling and tillage precision currently have a significant influence on both crop production and water management in Egypt. Frequently, farmers and government agencies do not have a full appreciation for the limitations of leveling and tillage precision on crop production and water management through irrigation uniformity. This study will provide information on the impact of leveling and tillage precision and recommend changes in current practices. This could have a major influence on water management in Egypt.

FUTURE PLANS: The SRFR model will be used to analyze the influence of leveling precision on recession times and thus irrigation uniformity. Statistical procedures are being developed so that these influences (recession only) can be added to the BASIN design program.

Further work will be conducted to develop a two-dimensional basin model that can handle an irregular bottom. This model will be used to determine the influence of land-leveling precision on irrigation uniformity from both advance and recession. These results will then be compared to the results based only on recession to determine under what conditions the influences on advance are significant.

A multiple furrow model also will be developed so that the influences of leveling and tillage precision can be evaluated for a field (i.e., a series of furrows). This new model will be an extension of the SRFR model.

Field irrigation evaluations will be performed for a season in Egypt under traditional and laser land leveling. These studies will provide basic information, which, combined with the results of the analytical work, will be used to make recommendations on the degree of land leveling precision necessary to achieve a desired level of irrigation performance and crop production.

Additional training will be provided during 1994 to Egyptian students in irrigation evaluations, instrumentation, and related topics.

COOPERATORS: Z. El-Haddad, M. El-Ansary, H. Osman, Department of Crops and Agricultural Engineering, College of Agriculture, Mostobor Zagazig University, Egypt; D. Fangmeier, U. of Arizona; and N. Katopodes, U. of Michigan.

WATER REUSE AND GROUNDWATER

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Increasing populations and finite water resources demand water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water.

APPROACH: Technology based on previous research at the USWCL and more recent research are applied to new and existing groundwater recharge and water reuse projects. Main purposes of the projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes.

Cooperative research has been initiated with The University of Arizona to manage clogging layers for optimum benefits in infiltration systems for groundwater recharge and soil-aquifer treatment where clogging layers are not wanted and in constructed wetlands, aquaculture ponds, and animal waste lagoons where clogging layers are wanted. Both hydraulic and water quality aspects will be considered.

FINDINGS: Initial field tests show that the area for a large Phoenix project is suitable for recharge with infiltration basins. Tests with experimental recharge shafts north of Scottsdale, Arizona, showed that recharge rates were within the range predicted on the basis of reverse augerhole theory.

INTERPRETATION: Results will be applied to existing and planned groundwater recharge and soil-aquifer treatment systems. Research proposals for funding by research foundations have been prepared. The first draft of a National Academy of Sciences report on groundwater recharge with low quality water has been completed. Various national and international conferences on groundwater recharge and soil-aquifer treatment are planned.

FUTURE PLANS: Future plans primarily consist of initiating and coordinating research on groundwater recharge and water reuse, and to respond to requests to write, speak, and give advice.

QUASI-POINT SOURCE ASSESSMENT: PESTICIDES AND NITRATES

H. Bouwer, Chief Engineer; and
A. J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Degradation of groundwater quality has been associated with extensive use of agricultural chemicals in many places throughout the United States. A study carried out by the EPA (EPA Rpt. 1990) showed that nitrate levels in 1.2% of community wells and 2.4% of rural domestic wells exceed the EPA's drinking water standard of 45 mg/ℓ Similarly, the study found that 10.4% of community wells and 4.2% of rural domestic wells have detectable levels of pesticides. Defining the sources of such chemicals in drinking water wells is essential for starting an effective water quality program. Sources of nitrate and pesticides may include local applications (point or farmstead source) and areal applications on fields (non point or field source) near a production well. The main objectives of this study are: (1) develop a method to determine if agricultural chemicals (pesticides and nitrates) observed in a well are from a point or non point source; and (2) develop a suitable remediation policy and recommend the best management practices to prevent contamination of the groundwater by agricultural chemicals.

APPROACH: Two approaches have been implemented to distinguish between different sources

(1) **Modeling Technique** - In the modeling technique an analytical solution has been used to model the transport of a contaminant in a three dimensional aquifer of infinite width and height with a patch solute source of finite-width and finite-height. The problem that this model aimed to answer can be stated as follows: "given a concentration hydrograph taken from a pumping well, what are the width and height of the contaminant source that may generate this observed hydrograph?". The program follows a search technique that can find the upper and lower limits of the observed concentration hydrograph using a range of model parameters. The program is linked to a graphic program to display the resulting hydrograph on the screen. The mathematical equations and the solution are explained in Wexler (1992).

(2) **Water Chemistry Identification Analysis** - To test the modeling technique, samples from an irrigation well (Cortaro-Marana Irrigation District well 18 [CMID]) in the Avra Valley, Arizona, were used to construct concentration hydrographs. In addition, inorganic chemical parameters and boron isotope ratios are being utilized to "*fingerprint*" the water from CMID 18 and from ground and surface waters thought to represent end-member compositions that may affect the groundwater at CMID 18. The element boron is essentially always present in water and the isotopic composition of boron can be used as an intrinsic tracer for various sources of groundwater contamination. Different water sources acquire characteristic isotopic ratios when fractionation events occur during the genesis of the source. Boron makes an excellent tracer because it exhibits relatively conservative behavior; thus with boron, the ratios that characterize a particular source remain constant as the contaminating water moves through the ground. Tracing the primary contaminants, nitrate and pesticides, without the use of a conservative tracer such as boron is often difficult because of chemical instability.

FINDINGS AND INTERPRETATIONS:

(1) **Modeling Technique** - The above modeling technique has been applied to the observed concentration hydrograph. The aquifer parameters are described as an interval; that is the aquifer velocity lies between 1 and 2 ft/d. Therefore, the output of the model is also in an interval form. The resulting upper and lower limits along with the observed hydrograph of the example problem are illustrated in Figure 1. This example problem shows that the observed concentration could be generated from a patch source 72.8 feet upstream from the well with a size of 16 by 16 ft. This program can be considered as a diagnostic tool to determine the size of the contaminant source.

(2) **Water Chemistry Identification Analysis** - Work has continued toward the characterization of groundwater chemistry at the Avra Valley field site. The analyses for inorganic anions in all samples have now been completed. In addition, the determination of δ^{11} has been completed for all samples taken during the first 100 acre feet of water pumped from CMID 18, and for many of the end-member source water samples.

Figures 2, 3, 4, and 5 summarize the results that have been obtained. Each figure represents the changes observed with respect to the cumulative volume of water pumped from well CMID 18 through the 1993 irrigation season. Chloride concentration (Fig. 2) and electrical conductivity (Fig. 3) exhibit similar trends of rapid increase immediately after the pump was first turned on (in March) followed by gradual increase as pumping continued. Sulfate concentration (Fig. 4) exhibits an inverted trend relative to chloride and EC. The sharp spikes in Figures 2, 3, and 4 represent samples collected immediately after the pump was turned on near the end of the irrigation season (in August). Although this sampling ensemble resembled that which was performed in March, the trends for all constituents were reversed. Also, where the changes during pumping in March occurred over days, the changes in August required only hours. Figure 5 indicates that the boron isotope ratios increased steadily over the course of the first 120 acre feet pumped. Analyses for δ^{11} later in the irrigation season, however, have not yet been completed.

The observed changes indicate a mixing of two waters with different compositions. Over the course of the irrigation season, a source of water is increasing the chloride and nitrate and decreasing the sulfate in the pumped water. These changes may be explained in two ways. First, the relative proportions of the two waters may have changed over the course of the irrigation season. Thus, the volume of water with high chloride and nitrate and low sulfate may increase as pumping continues. Second, the composition of the mixing waters may change over time. If the water that mixes with background groundwater changes over the course of the irrigation season, then such a change will be indicated in the mixed water composition

In either case, the quickness of change in water chemistry suggests that perched water flowing down the well bore may be the second mixing source. The presence of a perched zone has not yet been determined at CMID 18, but has been noted at other locations in the Avra Valley (Cuff and Anderson, 1987). The water in a perched zone in the vicinity of CMID 18 could theoretically originate from either irrigation return flow or from the effluent carried in the Santa Cruz River channel or from both sources.

FUTURE PLANS: In the modeling approach, the next step is to add different algorithms to cover a wide range of field situations and different kinds of contaminant sources which would allow the user decide which solution algorithm to choose.

To further apply the chemical identification technique, the inorganic chemistry and boron isotope ratio data from CMID 18 will be compared with data from potential end-member source waters to determine the impact of irrigation return flow and effluent flow in the Santa Cruz river on the pumped water composition. Work has also been initiated to determine if boron isotope signatures may be useful for differentiating between return flows from agricultural fields fertilized with different substances. Samples have been collected from the drainage tiles of three fields in Iowa, each of which has a consistent history of fertilizer application. One field had been fertilized with urea, one with anhydrous ammonia, and one with manure.

COOPERATORS: T. Maddock III, Professor, L. G. Wilson, Hydrologist; R. L. Bassett, Associate Professor; N.G. Shfike and J. Leenhouts, Research Assistants, The University of Arizona

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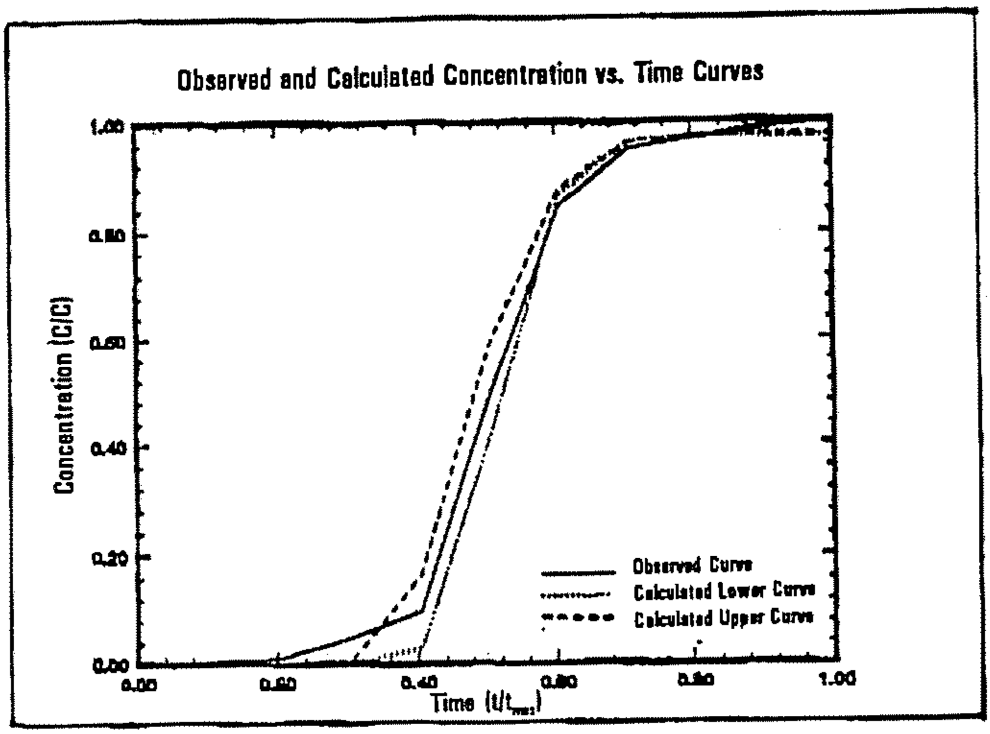

Figure 1. Observed and calculated breakthrough curves (upper and lower limit) for CMID well 18.

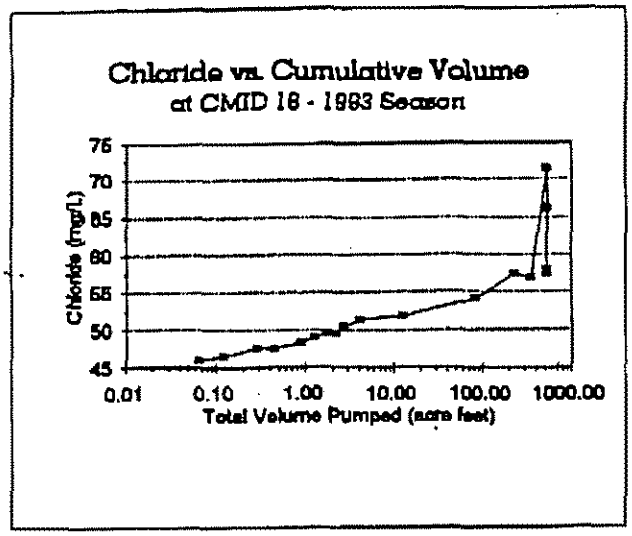

Figure 2. Changes in the chloride concentration of water from CMID 18 over the course of the 1993 irrigation season.

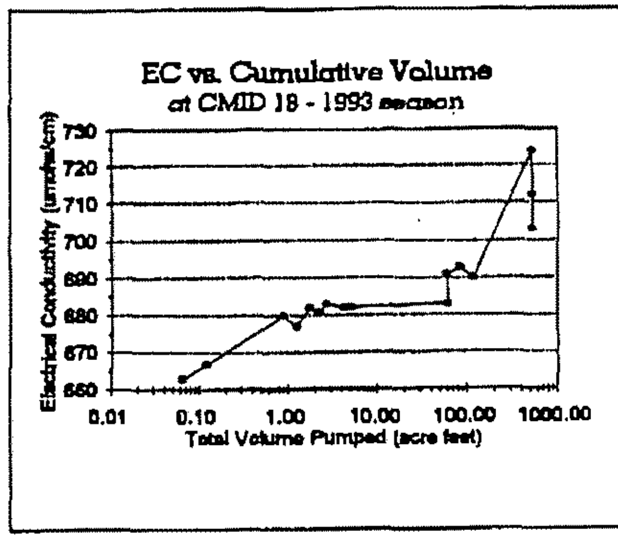

Figure 4. Changes in the electrical conductivity of water from CMID 18 over the course of the 1993 irrigation season.

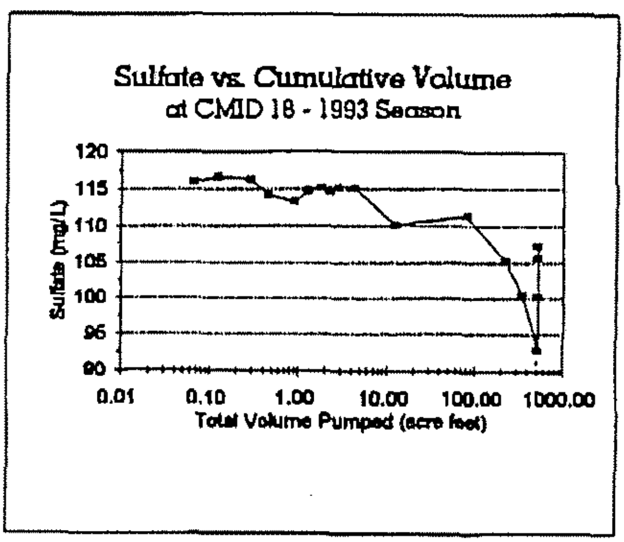

Figure 3. Changes in the sulfate concentration of water from CMID 18 over the course of the 1993 irrigation season.

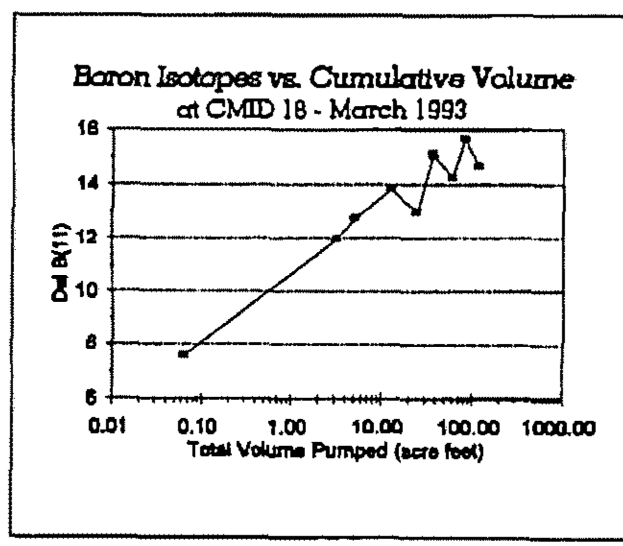

Figure 5. Changes in the isotopic signature of boron in water from CMID 18 during the first 100 acre feet of water pumped in the 1993 season.

PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF A SCHMUTZDECKE: EFFECTS OF SEEPAGE AND WATER TREATMENT IN WASTEWATER DISPOSAL FACILITIES

H. Bouwer, Chief Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Soil clogging occurs during artificial recharge and effluent disposal operations. Reduced infiltration and consequent ponding are attributed largely to development of a slime layer or "schmutzdecke" (De Vries, 1972; Rice, 1974). Paradoxically, significant water-quality enhancement may occur as water penetrates the schmutzdecke (Sims, 1987). Knowledge of the physical, chemical, and biological characteristics of schmutzdecke, it is hoped, will allow for adoption of management practices to either enhance or inhibit schmutzdecke development to meet the various goals of recharge or sewage treatment.

The objectives of the project are to determine (1) the physical, chemical, and biological processes occurring in the schmutzdecke; (2) the improvement of the water quality after it has moved through the schmutzdecke; (3) how schmutzdecke should be managed for specific needs (e.g., soil aquifer treatment, artificial wetlands); and (4) how compression of the schmutzdecke affects hydraulic and treatment characteristics.

APPROACH: Schmutzdecke are being developed in laboratory soil columns instrumented to measure redox potential, dissolved oxygen, and matric potential gradients. Alternate columns are flooded with filtered primary, secondary, and tertiary effluents. Quality parameters include dissolved organic carbon (DOC), adsorbable organic halide (AOX), nitrogen species, and pathogens. Three soil types will be tested: a sandy soil from Tucson Water's Sweetwater Underground Storage and Recovery (US&R) Facility, and silty and clayey soils from the Phoenix area. A second laboratory study is determining the hydraulic conductivity and compressibility of the schmutzdecke. Clogging layers will be developed from (1) one of the three soil types used during the study (i.e., sandy, silty, and clayey soils); (2) a layer of organic (effluent) solids and inorganic solids (suspended solids and dust); and (3) a layer (or layers) of algae identified from the site of Phoenix's proposed soil-aquifer treatment (SAT) project.

FINDINGS: Pertinent data will be collected and submitted in next year's report.

INTERPRETATION: The experimental design of the soil columns has been finalized, and preliminary flooding experiments are being conducted (see Figure 1 for experimental design). The first flooding experiment uses four soil columns packed with sandy soil from Tucson Water's Sweetwater US&R Facility. Columns are flooded with either secondary or tertiary effluents. The discharge from the columns is regulated to simulate infiltration rates and applied heads similar to those observed at the Sweetwater facility. After two weeks of continuous flooding, a sugar solution was added to accelerate the formation of a schmutzdecke. Significant quantities of bio-solids accumulated on the soil surface within two days. Water quality trends are pending.

A silty sand from Phoenix's proposed SAT site has been characterized for the following parameters: grain size, density, soil-moisture characteristics, and mineralogy. Water content, bulk density, and degree of saturation information has been collected for the near-surface soils, along with samples of a clogging layer.

FUTURE PLANS: Prototype soil column studies will be continued using alternative effluent sources, including filtered primary effluent, and secondary and tertiary effluent. Trials also will be conducted to determine treatment enhancement with ozonated effluent. The goal of these studies will be to (a) determine the effect of various water quality parameters (suspended solids [SS], assimilable organic carbon [AOC], and nutrients [nitrogen, phosphorus, potassium]) on the formation and properties of schmutzdecke; (b) determine the effects of the schmutzdecke on removal of contaminants; (c) distinguish between physico-chemical and bio-chemically moderated processes; and (d) establish management practices for specific needs. Dissolved oxygen/redox potentials, organic-carbon fractions, and matric potentials will be monitored with depth.

Impedance-related studies will include characterizing the particle-size distribution and soil-moisture characteristics of the soil from the Sweetwater US&R Facility, identifying algae types from the City of Phoenix SAT site, and studying the compressibility and hydraulic conductivity of clogging layers.

COOPERATORS: L.G. Wilson, Hydrologist, Robert Arnold, Assistant Professor, C.P. Gerba, Professor, Tracy Bogardus, Eric Ellman, Ed Miles, and David Quanrud, Research Assistants, University of Arizona; and Sandra Houston, Associate Professor, Peter Fox, Assistant Professor, and Peter Duryea, Research Assistant, Arizona State University.

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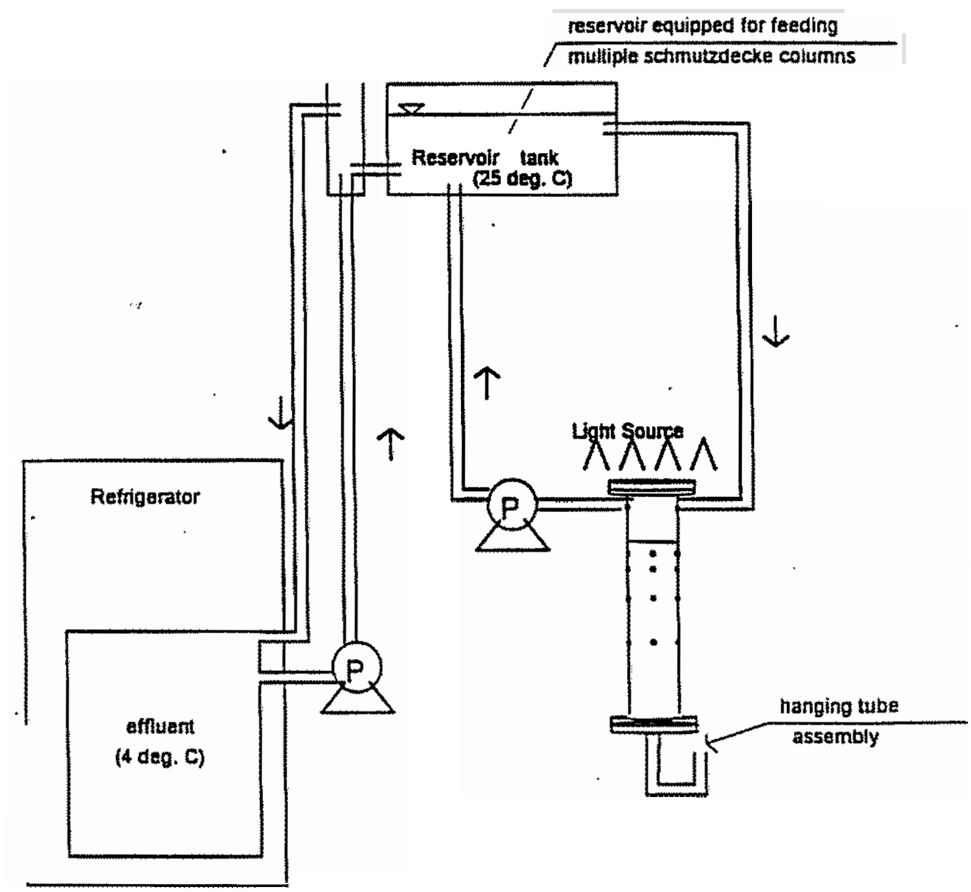


Figure 1. Flow schematic diagram for effluent supply to schmutzdecke columns. Applied hydraulic head is provided by a separate reservoir tank equipped for feeding multiple columns. Top of column is exposed to artificial light (GE gro-light). A hanging tube assembly is currently being used at the bottom of the column to maintain unit gradient through column profile.

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

R.C. Rice, Agricultural Engineer; F.J. Adamsen, Soil Scientist;
D.J. Hunsaker, Agricultural Engineer; H. Bouwer, Research Hydraulic Engineer;
and F.S. Nakayama, Research Chemist

PROBLEM: Agricultural chemicals used in irrigated crop production have been perceived as a threat to the quality of our groundwater supply. Rules and regulations governing the use of agricultural chemicals are becoming more restrictive. The rising trend in nitrate levels of groundwater suggests that nitrogen fertilizers are being transported beyond the beyond the root zone. Theoretically, irrigating at 100% irrigation efficiency will lead to zero deep percolation. Crop leaching requirements could be met when crops are not being grown and when most of the applied nutrients have been used by the crop. Studies conducted in 1991 and 1992 indicated that 100% irrigation efficiency during the growing season limited the transport of nitrogen to the vadose zone.

Current technology and knowledge of downward movement of agricultural chemicals to groundwater are inadequate because they do not consider spatial variability and preferential flow, and because the actual processes of physical, chemical, and biological attenuations are not adequately understood.

The objective of this study is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at 100% irrigation efficiency and to develop associated Best Management Practices (BMPs) to protect the quality of underlying groundwater. Particular emphasis is on establishing irrigation and nitrogen fertilizer management practices in hot, arid climates that are effective in reducing nitrogen leaching losses below the root zone and the role of preferential flow on water and nitrogen transport.

APPROACH: Studies on cotton and wheat grown using level basin flood irrigation were continued in 1993. The experimental design was a complete randomized block with six fertilizer-water application treatments and three replications. Each experimental plot was 108 m^2. A different conservative tracer was applied with each fertilizer application. Water movement in the soil profile was characterized with soil water content and tracer analysis. Evapotranspiration was estimated from energy balance techniques using meteorological data collected at the site.

Experimental treatments were as follows: 1) irrigation and fertilizer applications were scheduled according to current farm practices with 100% irrigation efficiency, 2) with 80% irrigation efficiency, and 3) with 20% deficit irrigation, 4) irrigation-applied fertilizer applications were scheduled according to residual soil, petiole NO_3-N feedback and with 100% irrigation efficiency, 5) with 80% irrigation efficiency, and 6) with 20 % deficit irrigation.

FINDINGS: Nitrate concentrations in the soil profile for wheat are shown in Figures 1 and 2. Each point represents the average of 18 samples. The nitrate level was greatest near the surface and decreased to low values at 60 to 90 cm. There appears to be no difference between the standard practice and BMP on tracer and nitrate movement. At 100% irrigation efficiency and deficit irrigation for both the standard and BMP treatments, however, less nitrate was leached below 100 cm. There was more NO_3-N in the profile below the root zone at 80% efficiency, indicating more leaching may have occurred at 80% efficiency. The deficit irrigation treatment had the least NO_3-N below the root zone.

INTERPRETATION: The results are similar to those of previous years, indicating that 100% efficiency irrigation during the growing season retains higher NO_3-N levels in the upper portion of the soil profile, resulting in less nitrogen loss by deep percolation.

FUTURE PLANS: The experiment will be repeated in 1994. Data from the transformation and mineralization of nitrate during the fallow period has been collected but not analyzed. Nitrate leaching under different irrigation methods (drip or sprinkler) will be investigated.

COOPERATORS: Dr. J.E. Watson, University of Arizona, Maricopa Agricultural Center, Maricopa, AZ.

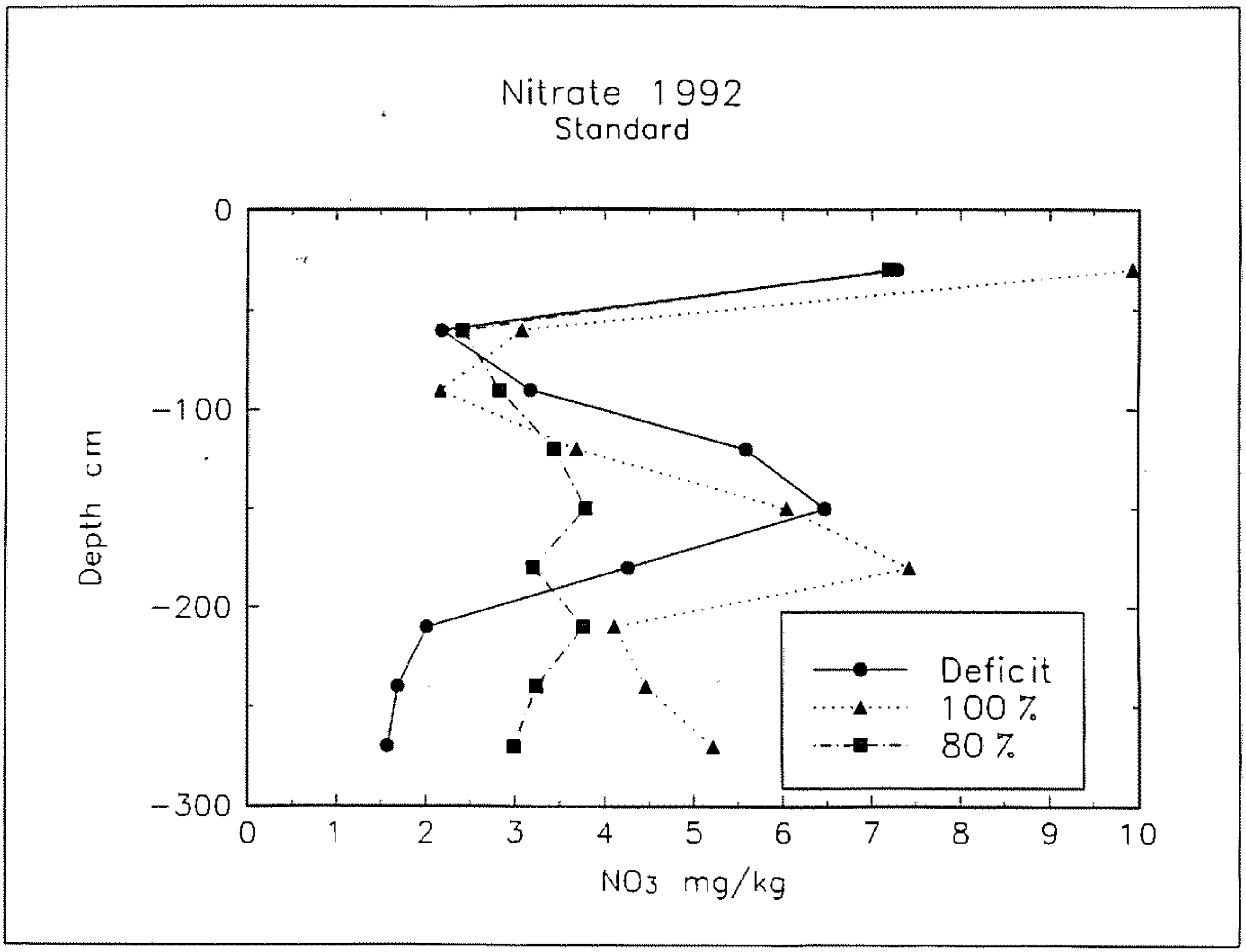


Figure 1. Nitrate concentrations for standard fertilizer application at 80 % and 100 % irrigation efficiency and deficit irrigation.

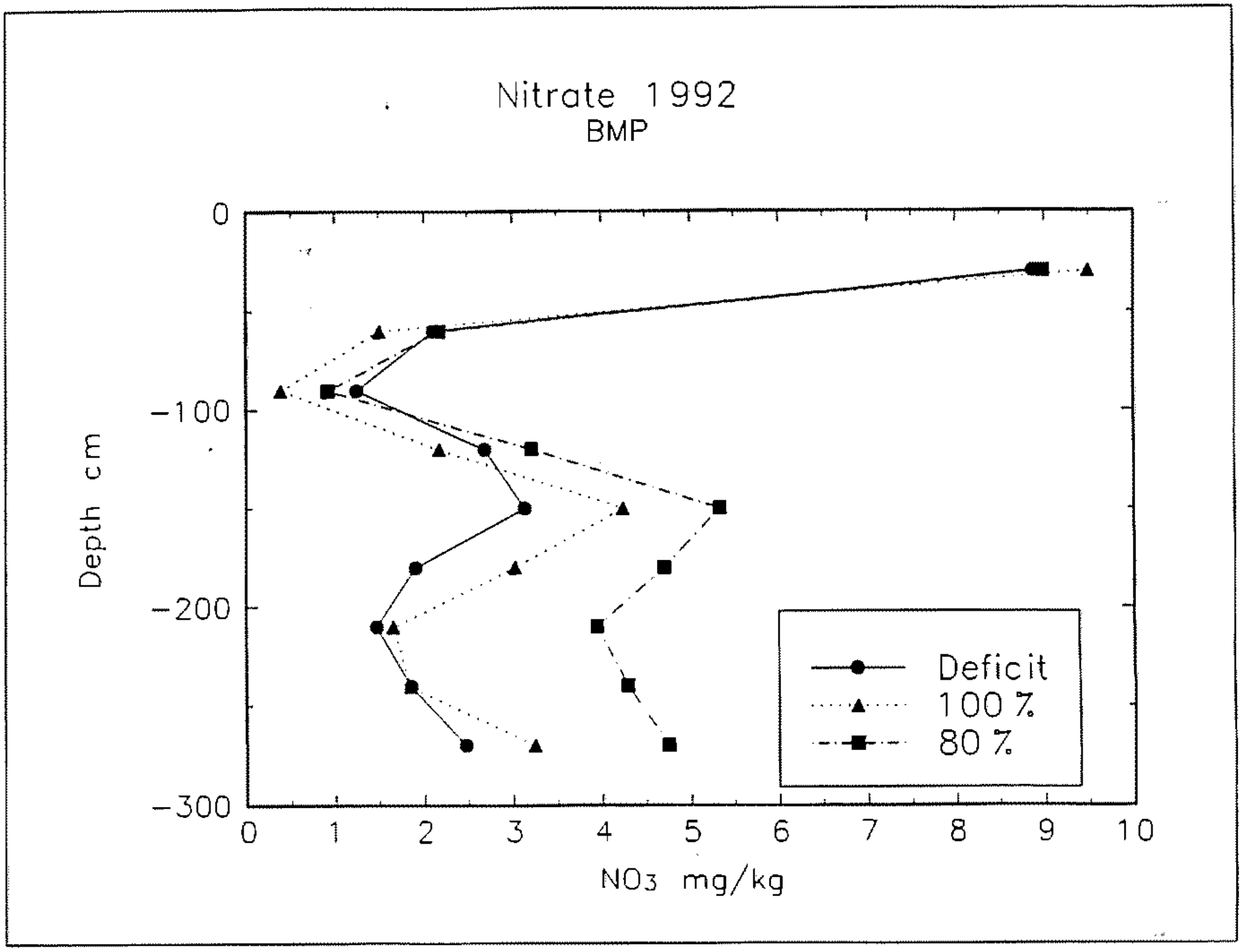


Figure 2. Nitrate and tracer concentrations for BMP fertilizer application at 80 % and 100 % irrigation efficiency and deficit irrigation.

NITROGEN BUDGETS OF IRRIGATED CROPS USING NITROGEN-15 UNDER HIGH EFFICIENCY IRRIGATION

F. J. Adamsen, Soil Scientist; R. C. Rice, Agricultural Engineer; F. S. Nakayama, Research Chemist; D. J. Hunsaker; Agricultural Engineer, and H. Bouwer; Research Hydraulic Engineer

PROBLEM: Nitrate is the pollutant most commonly found in groundwater. The contribution of nitrate to groundwater pollution carried by deep percolating irrigation water could be reduced or eliminated by the development of existing and new technologies. This requires a better understanding of the total nitrogen required by the crops produced and the timing of nitrogen uptake as well as chemical and water transport in the soil environment. Careful timing of fertilizer applications and prudent operation of irrigation systems to reduce the amount of water lost below the rooting zone can reduce the movement of water and chemicals to groundwater. Theoretically, irrigating at 100% efficiency and carefully controlling fertilizer amounts and timing of applications should lead to no deep percolation and no fertilizer leaching losses. Crop leaching requirements could be met when soil nitrate levels were lowest. However, because of spatial variability, preferential flow, and incomplete uptake of nitrogen by the crop, 100% irrigation efficiency and optimum nitrogen management may still produce some deep percolation and transport of nitrate to groundwater.

APPROACH: Research is being conducted through a series of experiments to evaluate irrigation efficiency theory and nitrogen management practices. Wheat was grown in the 1991-1992 and 1992-1993 seasons using level-basin flood irrigation. Wheat and cotton were planted in 1993. Future experiments will use other irrigation methods such as drip and sprinkler irrigation. The experimental design is a complete randomized block with six fertilizer-water application treatments and three replications. Experimental plots were approximately 81 m^2 in size in 1991 and 108 m^2 in 1992 and 1993. A different conservative tracer was applied with each irrigation, and nitrogen-15 tagged fertilizer was applied to three micro-plots in each main plot in 1991 and two micro-plots in 1992 and 1993. Micro-plots were approximately 1 m^2 in 1991 and 1992 and 1.5 m^2 in 1993. This allows a complete water and nitrogen balance, including the amount of nitrogen removed with the harvested crop, percolation losses, and volatile losses. The nitrogen status of the crop was determined by tissue analyses and leaf chlorophyll content with a chlorophyll meter. Chlorophyll measurements may allow a rapid, cost-effective method for determining the nitrogen status of a crop in real time and may be useful in determining the amount and timing of fertilizer nitrogen. Water movement in the soil profile is characterized by soil water content and tracer analysis. Evapotranspiration is estimated from energy balance techniques.

Experimental treatments include (1) a "standard" fertilizer and irrigation management procedure where irrigation and fertilizer applications are scheduled according to current farm practice with irrigation amount as 100% of estimated evapotranspiration (ET); (2) same as treatment 1 except with 120% of ET; (3) same as treatment 1 except with a deficit irrigation equivalent to 80% ET; (4) irrigation water applied fertilizer application (chemigation) scheduled according to residual soil, petiole NO_3-N feedback, and leaf chlorophyll content with irrigation amount as 100% of ET; (5) same as treatment 4 except with 120% of ET; and (6) same as treatment 4 except with a deficit irrigation equivalent to 80% ET.

FINDINGS: In 1992-1993 wheat, the standard fertilizer treatment was 45 kg ha^{-1} applied broadcast at planting as $(NH_4)_2SO_4$ and an additional 95 kg ha^{-1} of N applied in the irrigation water. The BMP nitrogen treatment was 45 kg ha^{-1} applied at planting and an additional 64 kg ha^{-1} applied in two applications in the irrigation water. The winter of 1992-1993 was wetter than normal, and, as a result, there was little demand for irrigation water during vegetative growth. The spring rainfall was nearer normal than in 1992, and there were differences in the amounts of water applied during grain fill.

Overall, grain yields averaged over 5600 kg ha^{-1} (Table 1). Yields from BMP plots were lower than those from the standard fertilizer treatment, suggesting that nitrogen was limiting in the BMP treatments. Water did not appear to affect grain yields as much as fertilizer treatment.

In 1993 cotton, the standard fertilizer treatment was 97 kg ha^{-1} applied broadcast at planting as $(NH_4)_2SO_4$ and an additional 108 kg ha^{-1} applied in the irrigation water. The BMP nitrogen treatment was 32 kg ha^{-1} applied broadcast at planting and an additional 108 kg ha^{-1} applied in two applications in the irrigation water. Rainfall for the summer of 1993 was below normal. The irrigation treatments received differing amounts of irrigation water throughout the entire growing season.

In general, lint and seed yields increased as water increased (Tables 2 and 3). The exception to this was standard fertilizer at 80 and 100% ET. In this case, for both lint and seed, yields were higher with application of irrigation water of 80% ET than with application of 100% ET.

Results of nitrogen-15 analyses of wheat from the 1991-1992 crop year show that approximately half of the nitrogen in both grain and straw was derived from the added fertilizer. Nitrogen-15 analyses of soil samples taken after harvest showed that small amounts of fertilizer nitrogen moved below the root zone in all treatments. In the treatment with the largest application of water, 120% ET, there appears to be less fertilizer nitrogen remaining in the soil from plots that received the standard fertilizer application than in soil from plots receiving the BMP fertilizer treatment (Figs. 1 and 2).

INTERPRETATION: The apparent response of 1992-1993 wheat yields to fertilizer levels suggests that current BMPs for nitrogen may need to be modified. Producers will be reluctant to adopt practices that result in lower yields unless there is a significant reduction in input costs. The apparent lack of response by wheat to irrigation amounts is promising because nitrate can be retained in the root zone by controlling irrigation. Cotton, on the other hand, had the opposite response in 1993. Cotton yields decreased with decreasing water application, but were not affected by the fertilizer program used. This suggests that reducing water inputs may not be an effective method of reducing nitrate movement but improved timing of both water and nitrogen, (i.e., more intensive management), may be needed to control nitrate movement below the root zone in cotton.

Nitrogen-15 data show that water and fertilizer-derived nitrogen are moving below the root zone in all treatments. Improved water management appears to reduce nitrogen losses.

FUTURE PLANS: In 1994 the studies on wheat and cotton will be continued. Additional irrigation methods also need to be investigated. The rates of movement of chemical tracers and labelled nitrogen will be used to assess the impact of preferential flow. The data set should be suitable for evaluating current soil models which predict the quality of water moving below the root zone. If no suitable models exist, a model development and verification effort can be initiated.

COOPERATORS: J. E. Watson, The University of Arizona Maricopa Agricultural Center; T. L. Thompson, The University of Arizona Department of Soil and Water Science.

Table 1. Yield of wheat from the 1992-1993 from the irrigation and fertilizer management study.

Nitrogen Application Method	80 % ET	100 % ET	120 % ET	Average
	kg ha^{-1}			
Standard	6003	5903	5749	5885
BMP	4845	5513	5847	5401
Average	5424	5708	5798	5643

Table 2. Lint yield of cotton from the 1993 irrigation and fertilizer management study.

Nitrogen Application Method	80% ET	100% ET	120 % ET	Average
	kg ha^{-1}			
Standard	833	591	1017	814
BMP	559	818	1183	853
Average	696	704	1100	833

Table 3. Seed yield of cotton from the 1993 irrigation and fertilizer management study.

Nitrogen Application Method	80% ET	100% ET	120 % ET	Average
	kg ha^{-1}			
Standard	1731	1343	2152	1742
BMP	1333	1734	2254	1774
Average	1532	1539	2203	1758

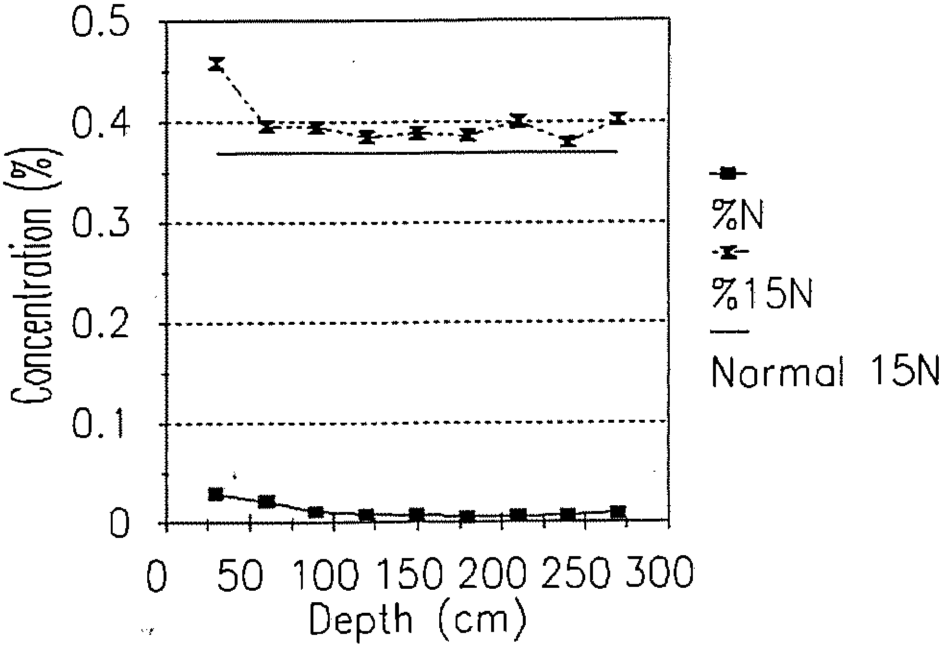


Figure 1. Concentration of nitrogen and nitrogen-15 in soil from 1991-1992 wheat plots with 120% ET irrigation treatment and standard fertilizer application. Normal nitrogen-15 = 0.37%

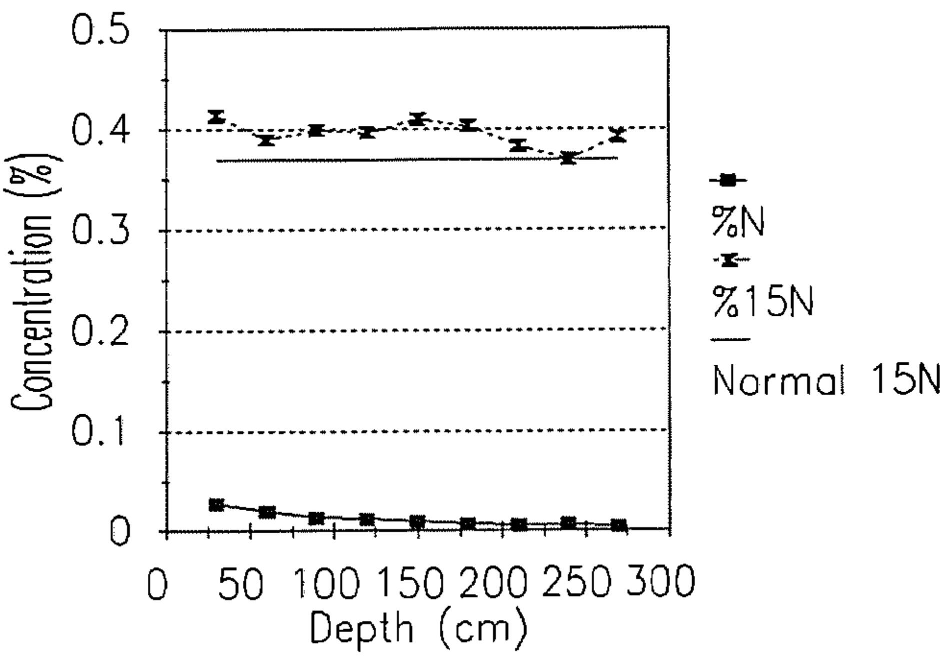


Figure 2. Concentration of nitrogen and nitrogen-15 in soil from 1991-1992 wheat plots with 120% ET irrigation treatment with best management practice fertilizer application. Normal nitrogen-15 = 0.37%.

EVALUATION OF RAPE AND CRAMBE AS POTENTIAL WINTER CROPS TO REDUCE NITRATE ACCUMULATION IN THE SOIL

F. J. Adamsen, Soil Scientist; W.L. Alexander, Agronomist; and R.C. Rice, Agricultural Engineer

PROBLEM: *Formation of nitrate during fallow periods* in irrigated cotton rotation systems can lead to leaching of nitrate to groundwater when preplant irrigations are applied in order to make the soil suitable for tillage operations. One solution to this problem is growing a winter crop that utilizes residual nitrogen and nitrate mineralized during the winter. Due to the cost of water, any crop grown in the winter under irrigated conditions must have an economic return in order to gain producer acceptance. *This means that a crop must be found that can* be planted after cotton is harvested in the fall and can be harvested before cotton is planted in the spring. Two crops which may meet these restrictions are rape and crambe. Industrial rape and crambe both contain erucic acid which has industrial potential and Canola types of rape are valuable as sources of unsaturated cooking oil. Both of these crops are short cool season crops that may meet the short growing season requirement and have a significant nitrogen requirement that would take advantage of residual nitrogen in the soil.

APPROACH: Research is being conducted through a series of field experiments to evaluate yield potential and maturity dates of rape and crambe. Two varieties of winter type industrial rape were planted in the 1992-1993 growing season on 0.1 acre plots. For the 1993-1994 growing season, one variety of crambe, one variety of spring type industrial rape, and eight varieties of spring Canola types of rape will be planted in 2 X 12.2 m plots with three planting dates from late October through early December.

FINDINGS: In 1992-1993 one of the varieties of winter type industrial rape was eaten by birds and rodents shortly after emergence. The crop matured late May which was the same time as wheat. Harvest was a problem with rape because the pods shatter if left on the plant; therefore, the crop needs to be windrowed when pods begin to mature to prevent loss of seeds. The appropriate equipment was not available to windrow the crop, so we were unable to obtain yield data. However, the plants that were not eaten by pests grew well with no apparent disease or insect problems.

INTERPRETATION: The winter types of rape matured too late in the spring to allow planting of full season cotton. Due to white fly pressure, most producers would be unwilling to plant cotton after harvesting rape because the resulting crop would mature too late in the fall. The spring varieties of rape and crambe should mature earlier than the winter types, but there are not many spring industrial types of rape available. While there is a market for Canola for oil, industrial rape may be a better nitch crop for irrigated agriculture because there is less competition; and this area is isolated from edible oil production, which protects edible oil producers from crosses between industrial and edible types. Crosses result in oil of intermediate concentrations of erucic acid which is of reduced value in both markets.

FUTURE PLANS: In 1994 evaluation of rape and crambe will be continued. Early maturing varieties of rape from the Georgia breading program, one variety of industrial rape from Agrigentics, and one variety of crambe from the North Dakota breeding program will be grown in a planting date study. The results of the planting date by variety trial will be used to develop a rotation system with cotton that will provide year-round cover on the soil and should improve year-round nitrogen management.

COOPERATORS: Paul Raymer, Coastal Plain Experiment Station, Tiffton, Georgia; Larry Sernek, Agrigenetics, Madison, Wisconsin; Jennifer Mitchell Fetch, University of North Dakota, Fargo, North Dakota.

ASSESSMENT OF NITRATE LEACHING UNDER COMMERCIAL FIELDS

F. J. Adamsen, Soil Scientist; and R. C. Rice, Agricultural Engineer

PROBLEM: Application of excess nitrogen to crops such as cotton and subsequent application of excess irrigation water can result in movement of nitrate to groundwater. When nitrate is found in groundwater, agriculture is usually assumed to be the source of contamination. A number of surveys of midwest fields indicate that farm practices are responsible for at least part of the nitrate that finds it way into groundwater. Under irrigated conditions, nitrate leaching is a function of irrigation efficiency and spacial variability as well as fertilizer management, which make assessment of the problem more complex.

APPROACH: Research is being conducted by taking soil samples from commercial fields after a crop has been harvested. Three transects are taken across each field with five samples taken in each transect. Spacing of samples along the transect was based on the length of the run. The first sample was taken 10% of the of the run length from the top of the field. The next four samples were taken 20% of the run length apart. The positions in the transect are numbered from one to five starting at the upper end of the field. Samples are taken to a depth of 270 cm and analyzed for ammonium, nitrate, and texture. In 1993, samples were taken from two fields on one farm. Both fields were planted to cotton. The length of run on field 3C was approximately 245 m, and field 10 was approximately 480 m. In July 1993, surface soil samples were taken on the first and the seventh, which was before and after a nitrogen application. The producer applies fertilizer in the irrigation water during the last two hours of the irrigation. Unlike most chemigation systems, the producer adds dry fertilizer to the water which may reduce the uniformity of application.

FINDINGS: The July samples were taken to determine the effect of the producers' fertilizer application methods on the concentration of inorganic nitrogen in the surface soil. The producer had determined that an application of nitrogen was necessary to complete the crop. Overall, the changes were smaller than expected; and there were some decreases of total inorganic nitrogen in the surface soil (Figs. 1 and 2). In most cases negative changes were decreases in nitrate, which indicates that the irrigation water leached the nitrate from the surface. In some cases, there were changes of more than 60 mg/kg of soil. Changes of this magnitude are probably due to sampling anomalies on either the first or second sampling period. Total inorganic nitrogen in field 3C was higher in furrows closest to the source of nitrogen, suggesting that mixing was incomplete and gradient flow occurred in the ditch during fertilizer addition.

Samples taken in October were intended to determine the effectiveness of the water and fertilizer management system. Differences in ammonium content were correlated to differences in texture because the ammonium ion is held by clay and organic matter and the results were similar for both fields. Nitrate concentrations were higher in samples from field 10 than those from field 3C, especially at the lower end of field 10. Both fields had transacts that showed little or no nitrate leaching, and some transacts which indicated movement of nitrate below the root zone (Fig. 3 and 4). In general, nitrate leaching appeared to be highest in lower end of each field although there were some samples that showed leaching losses in the center and upper portions of the field (Figs. 3b and 4b).

INTERPRETATION: Results from the surface samples taken before and after fertilizer application indicate the level of nitrate in the soil surface may not be a good indicator of the nitrogen needed by the system. Plant levels of nitrogen and chlorophyll content of the leaves may be better indicators. The system used by the producer for nitrogen application appeared to work better in field 3C where the run was shorter than in field 10. There was evidence of nitrate leaching in both fields that appeared to be the result of spacial variability and of application inefficiency. It appears that short fields have fewer problems with application efficiency. Overcoming spatial variability problems that affect fertilizer and water applications will probably require changes in irrigation amounts or application methods. Applying nitrogen in the irrigation water makes site-specific management impractical.

FUTURE PLANS: In 1994, the study will be expanded to include additional producers. Selection of additional sites will be based on the crop rotations, soil type, and irrigation method. The study also will be expanded to include sites in the Yuma area.

COOPERATORS: Buddy Ekholt, Pinal County Irrigation Management Program; T. L. Thompson, University of Arizona, Dept. of Soil and Water Science

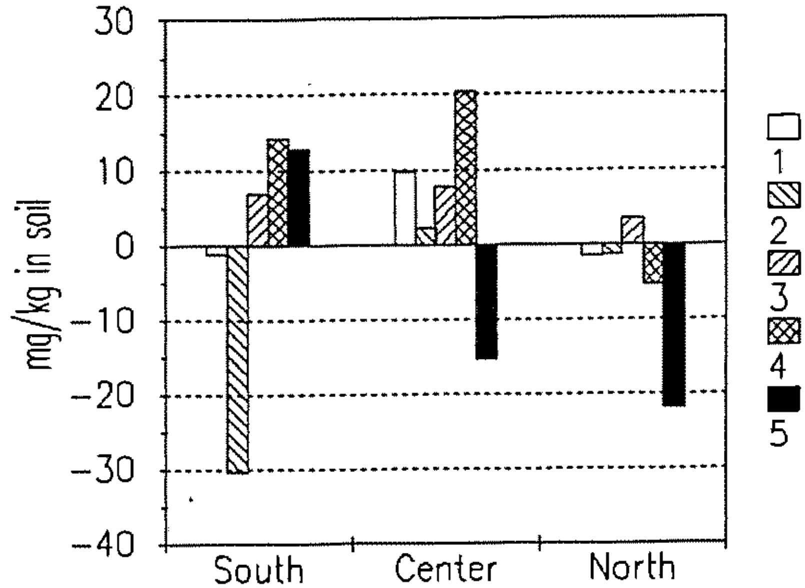


Figure 3. Change in total inorganic nitrogen in the surface soil of field 3C between July 1 and July 7, 1993, positions 1 to 5 starting at the top of the field.

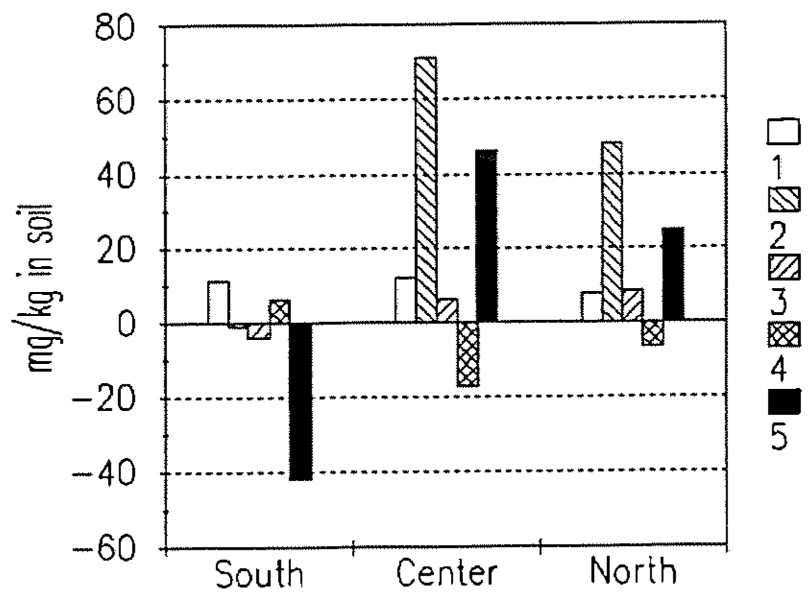
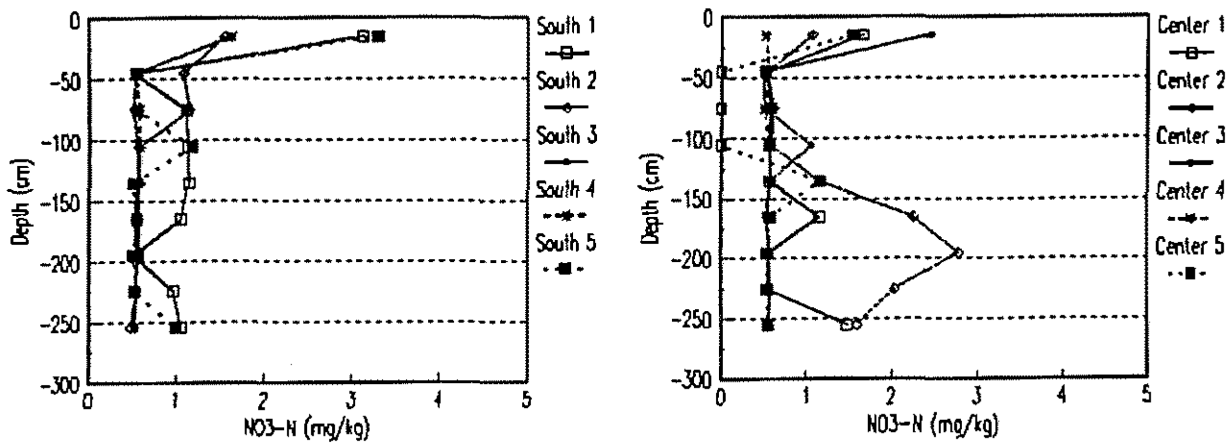
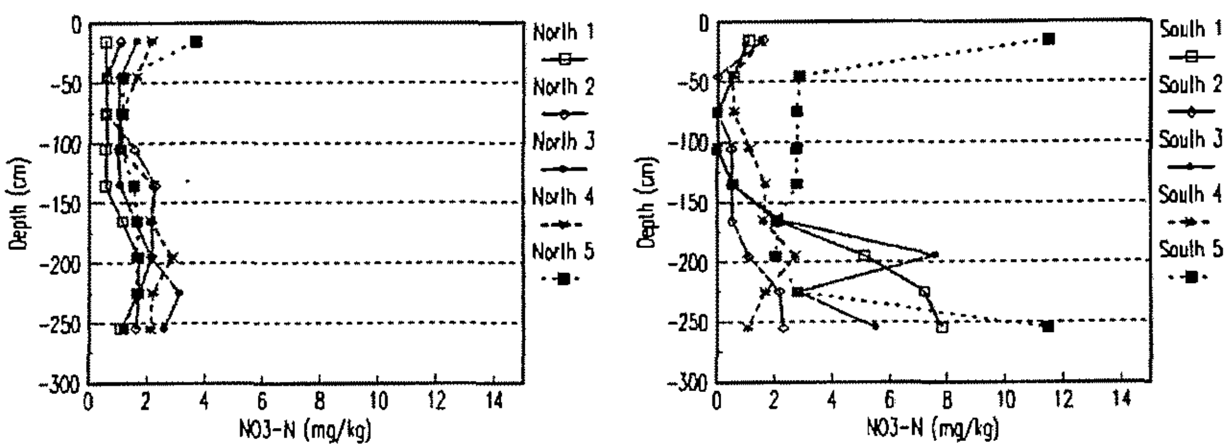


Figure 4. Change in total inorganic nitrogen in the surface soil of field 10 between July 1 and July 7, 1993 positions 1 to 5 starting at the top of the field.



(a) (b)

Figure 3. Nitrate concentration of soil from field 3C from the (a) south transect and (b) center transect, positions 1 to 5 starting from the top of the field.



(a) (b)

Figure 4. Nitrate concentration of soil from field 10 from the (a) north transect and (b) south transect, positions 1 to 5 starting from the top of the field.

SIMULATION OF CHEMICAL TRANSPORT IN SOILS FROM SURFACE IRRIGATION

T.S. Strelkoff, Research Hydraulic Engineer; F.J. Adamsen, Soil Scientist; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Irrigation management influences the quality of both surface and groundwater supplies. Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in the course of agricultural operations; and naturally occurring, selenium, for example, all can be transported to surface or subsurface water supplies by the movement of irrigation water, to the detriment both of human consumers of the water resource and wildlife dependent on these bodies of water.

The transport, transformation, and ultimate fate of chemical components of the irrigation water depend on the quantities of water remaining in the root zone after the irrigation, the quantities running off the ends of the fields into drainage ditches and canals, and the quantities that continue to percolate through the soil, eventually entering either a groundwater aquifer or a river fed from groundwater seepage. The chemical and physical reactions among the water, the soil medium, and the particular chemicals involved significantly influence the transformation and ultimate fate of the chemical constituents.

Preferential flow, fingering of the water front advancing downward through the soil medium, occurs both as the result of nonhomogeneous soil with worm and root channels, and layering of soils with a layer of low permeability overlying one of great permeability. This results in more rapid transport of waterborne constituents to the groundwater table.

In the porous subsurface medium, many existing models view variation in only one dimension, the vertical, assuming no movement parallel to the stream flow. However, *interflow* is known to occur, especially on steep slopes, and, in fact, provides the principle means of transport of groundwater, along with its chemical constituents, into surface streams.

The goal of this research effort is a predictive tool, a computer model, capable of simulating the response of a given agricultural field and its geologic site to one or another irrigation management practice. Computer simulations would allow swift comparisons among various trial management modes in a program to seek optimum solutions. This would make possible recommendations on the basis of environmental considerations as well as upon water conservation and crop yield.

APPROACH: Two different problems comprise the subject of investigation: (1) transport of a contaminant by irrigation water from a contaminated soil-surface layer to stream flow and to the groundwater via deep percolation, and (2) the longitudinal distribution of a chemical introduced nonuniformly in the irrigation-inflow hydrograph; e.g., a pulse of chemical introduced at some time after the start of water inflow at a constant rate.

Both problems are to be treated by a plane two-dimensional mathematical simulation, coupling a solution of the Navier-Stokes equations augmented with a two-equation turbulence model in the surface stream to a solution of the equations for unsaturated flow in a porous medium in the underlying soil. The two regions share a common vertical velocity field at the interface. The free surface of the deforming finite-element grid used in the simulation is found from the kinematic boundary condition on the equations of motion. The shear calculated at the channel bed is used to determine incipient sediment motion. The air-water-soil singularity at the wave front is replaced by a finite segment of arbitrarily short length treated as a zero-traction outflow boundary.

Mass transport is modeled in the entire system through dispersivities calculated from the flow equations. Sorption and desorption are incorporated in terms of both equilibrium and nonequilibrium kinetics of semi-empirical determination. The same is true for volatilization, degradation, and leaching processes, incorporated as sink terms in the mass transport model.

A physical model with a graded sand bed is contemplated for verification of the mathematical model.

FINDINGS: Various approaches for handling the troublesome aspects of surface-wave propagation have been implemented. Three versions of wave-front construction and advance are now available. One has the wave move on an existing film of water, the other two on a dry bed. The first limits element deformation by allowing nodal shifts only in the vertical direction and constitutes the most robust version but is not yet complete. The other two techniques allow arbitrary movement of nodes by tracking either markers placed within the elements or the nodal coordinates themselves. Both of these approaches are operational but are fragile and often lead to instability and simulation failure.

The k-ϵ turbulence model has been slightly modified by employing the square roots of these turbulence parameters instead (so called q-r model). This has improved the convergence of the iterations. Large Eddy Simulation (*LES*) is also in experimental use -- significant savings in execution time will result if it works.

The subsurface-flow model has experienced the greatest advance. The computations are now performed on a moving finite-element (MFE) model. This allows a dynamic computational grid with the highest resolution centered at the air-water-soil interface and constitutes an optimum distribution of elements that follows the dynamics of the problem. The code also has been modified to a Petrov-Galerkin Streamline Upwind (SUPG) scheme to avoid instabilities at the wetting front. Finally, a subroutine, CONVERT, has been written to convert the nine-node element results of the surface model to the four-node elements compatible with the subsurface and mass-transport model.

The interface layer based on the staggered array of cylinders has been abandoned. Though it still has some theoretical appeal, it has not proved possible to integrate it with the surface and subsurface models.

A search of the experimental literature indicates very few well-controlled laboratory studies dealing with contaminant transfer and transport by overland flow. Graduate students with backgrounds in hydraulics, open-channel flow, soil chemistry, and sediment transport have been selected to construct an experimental facility and perform the initial round of studies. Preliminary designs have been achieved in joint meetings between University and Laboratory personnel.

INTERPRETATION: The simulation model is too new to have yielded significant results to date. It shows promise, however, in being capable of simulating the subject phenomena to a useful degree. With increased reliability and verification, it should serve both as a research tool in evaluating irrigation management and as a theoretical base for more approximate, more practical simulations.

FUTURE PLANS: The mathematical model will be exercised over a range of practical conditions to establish and strengthen its reliability. Specific chemical constituents to be incorporated into the model will be selected, along with currently available figures on reaction kinetics, to substitute for the present hypothetical assumptions. The physical flume will be built and operated to test the various model assumptions, establish appropriate values for numerical solution parameters, and verify its performance.

COOPERATORS: N.D. Katopodes, University of Michigan, Ann Arbor, MI; Mark L. Brusseau, The University of Arizona, Tucson, AZ.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON THE ENERGY BALANCE AND EVAPOTRANSPIRATION OF WHEAT

B.A. Kimball, Supervisory Soil Scientist; R.L. LaMorte, Civil Engineer;
R. Seay, Agricultural Research Technician; C. O'Brien, Biological Aide;
P.J. Pinter, Jr., Research Biologist; G.W. Wall, Plant Physiologist;
R.L. Garcia, Plant Physiologist; D.J. Hunsaker, Agricultural Engineer;
and R. Rokey, Biological Technician

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (*ET*), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. One important objective of this experiment was to evaluate the effects of elevated CO_2 on the ET of wheat.

APPROACH: The evapotranspiration measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project, which sought to determine the effects of elevated CO_2 on plant growth, yield, and many physiological processes, as well as water use. Four toroidal plenum rings of 25 m diameter constructed from 12" irrigation pipe were placed in a wheat field at Maricopa, Arizona, shortly after planting. The rings had 2.5 m high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching CONTROL rings at ambient CO_2 but with no air flow also were installed in the field.

The determination of the effects of elevated CO_2 on *ET* by traditional chambers is fraught with uncertainty because the chamber walls that constrain the CO_2 also affect the wind flow and the exchange of water vapor. Therefore, a residual energy balance approach was adopted, whereby *ET* was calculated as the difference between net radiation, R_n; soil surface heat flux, G_0; and sensible heat flux, H: $\lambda ET = R_n - G_0 - H$. R_n was measured with duplicate net radiometers, and G_0 with soil heat flux plates. H was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with duplicate infrared thermometers (IRTs) mounted above each plot. The net radiometers and IRTs were switched weekly between the FACE and CONTROL plots.

FINDINGS: Figure 2a shows the hourly patterns of weather variables for one mid-season day, March 16, 1993. Foliage temperatures were typically about 3°C cooler than air temperatures except from dawn until about noon. FACE foliage temperatures averaged 0.4°C warmer than CONTROL temperatures on this day.

R_n (Fig. 1a) was the largest component of the energy budget on March 16, 1993, generally much larger in magnitude than G_o (Fig. 1b) or H (Fig. 1c). Consequently, λET (Fig. 1d) tended to follow R_n. The error bands on R_n were tight, and differences in R_n between FACE and CONTROL were small (Fig. 1a). Consequently, effects of FACE on λET were also small, averaging less than 5% on this particular day.

FACE tended to increase the wheat canopy temperatures, by an average 0.56°C from February through April, which made the crop slightly less cool than air temperature most of the time (data not shown).

Daily FACE R_n averaged 4% less than CONTROL R_n from mid-January through April (data not shown). Furthermore, the error bounds were tight with no evidence of changes in treatment effects when the instruments were switched weekly between FACE and CONTROL. Daily totals of G_o were very small (generally < 1 MJ m^{-2} day^{-1}), as expected. Daily FACE H tended to be smaller in magnitude than CONTROL H, which means it was less negative on most days. This tendency was because the FACE plants were slightly warmer than the CONTROLs most of the time, and both FACE and CONTROL plants generally were cooler than the air except from about dawn until noon (Fig. 2a).

Daily FACE λET was less than that of the CONTROL plots most of the days (Figs. 2b, 2c). At the end of the season in May, the FACE plants matured earlier, leading to larger differences in λET. Excluding these May data, the regression of FACE on CONTROL λET from mid-January through April (Fig. 2c) indicates that the FACE treatment decreased λET by an average 11%.

INTERPRETATION: It appears from these data that irrigation requirements for wheat may be somewhat lower in the future high-CO_2 world (provided that any global warming is small).

Also, the observation that FACE caused foliage temperatures to be increased by 0.56°C day and night all season long may be the cause of the accelerated maturity and senescence of the plants in the FACE plots.

FUTURE PLANS: Current plans are to replicate the 1992-3 experiment in 1993-4. Micrometeorological parameters required to evaluate the energy balance and evapotranspiration will again be measured.

COOPERATORS: See report on "Progress and plans for the free-air CO_2 enrichment (FACE) project."

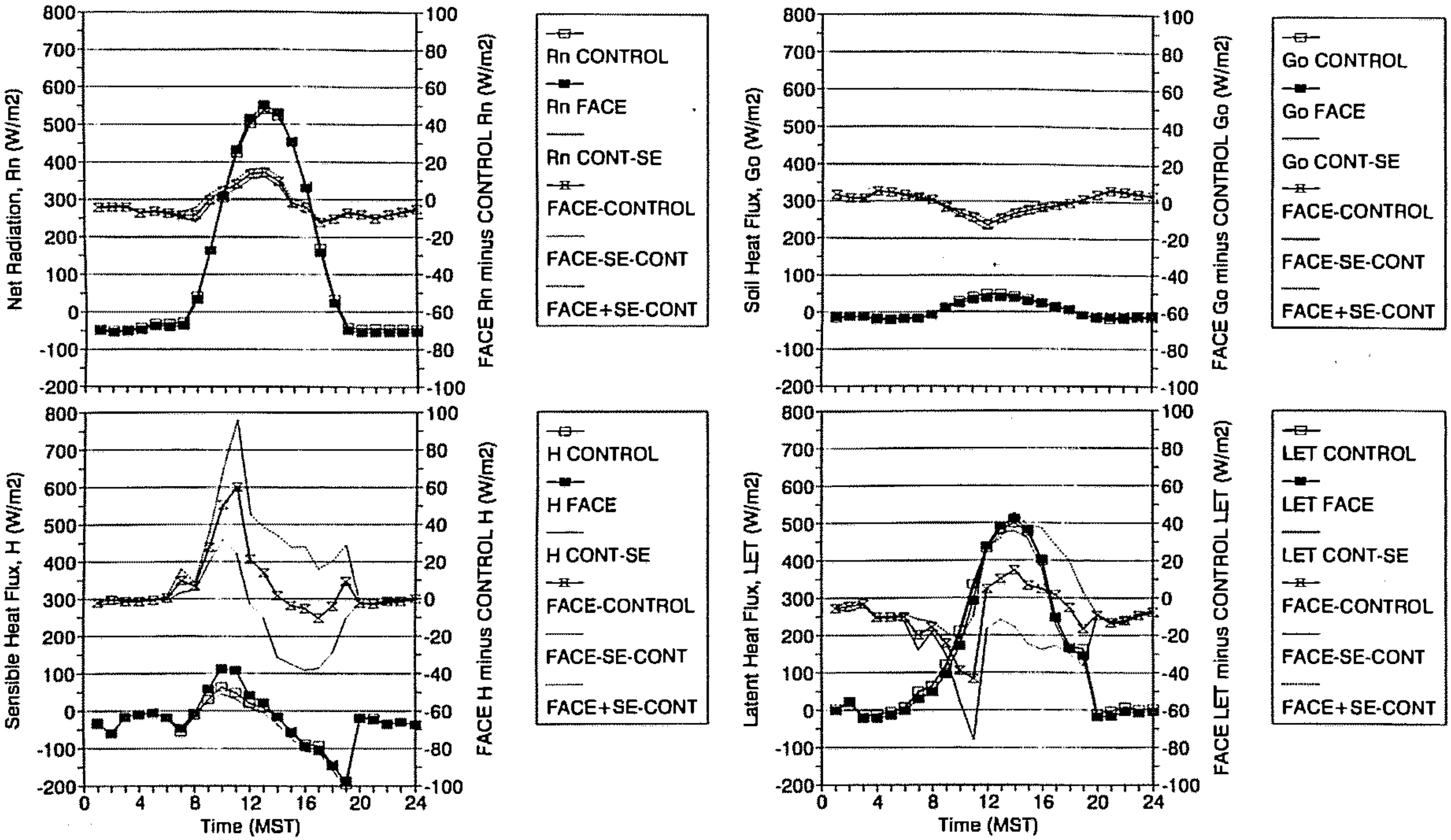


Figure 1. Diurnal patterns of (a) net radiation, (b) soil heat flux, (c) sensible heat flux, and (d) latent heat flux on March 16, 1993 (day-of-year 075) during the 1992-3 FACE Wheat experiment. Also shown on the right axis are the respective differences between FACE and CONTROL plots, as well as some of the standard error bands.

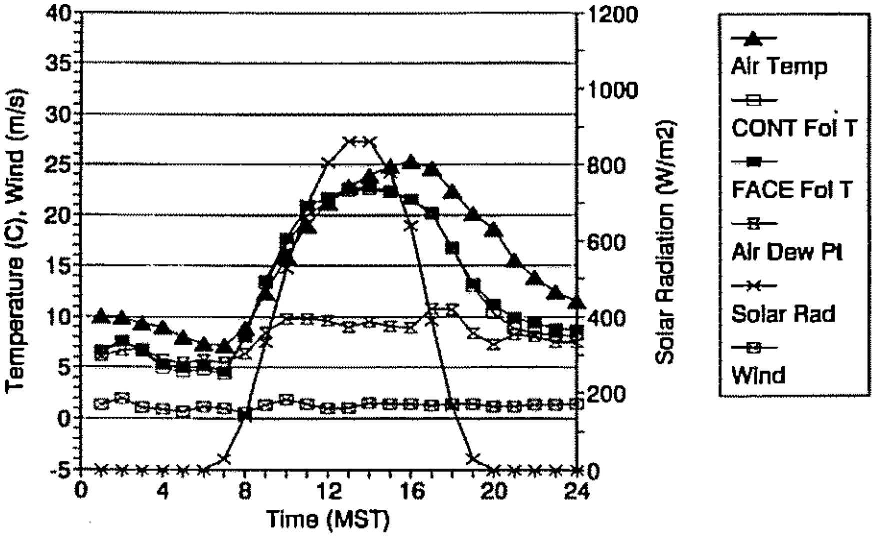


Figure 2a. Diurnal patter of air temperature, foliage temperature in CONTROL and FACE plots, air dew point, solar radiation, and wind speed for March 16, 1993.

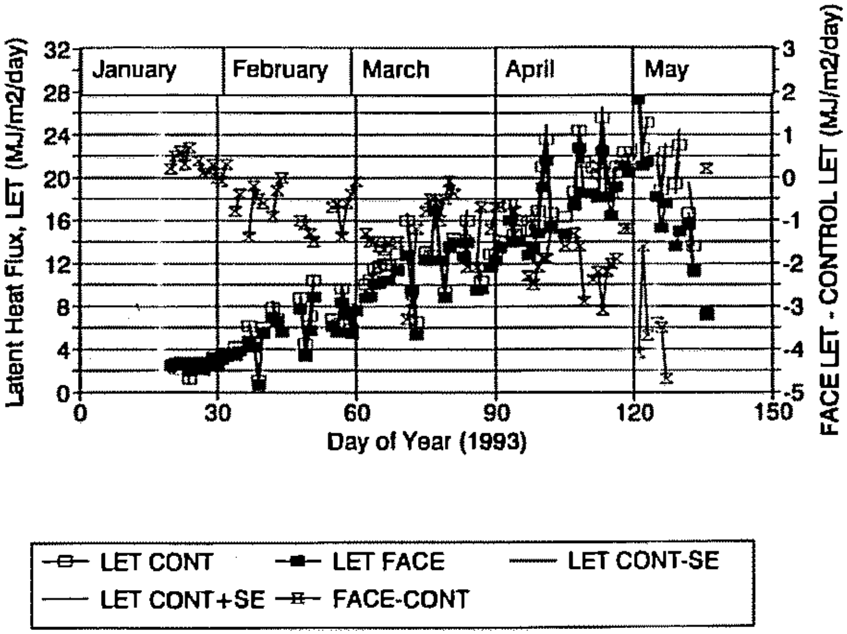


Figure 2b. Daily latent heat fluxes in the CONTROL and FACE plots and their differences versus day-of-year for the FACE Wheat 1992-3 experiment.

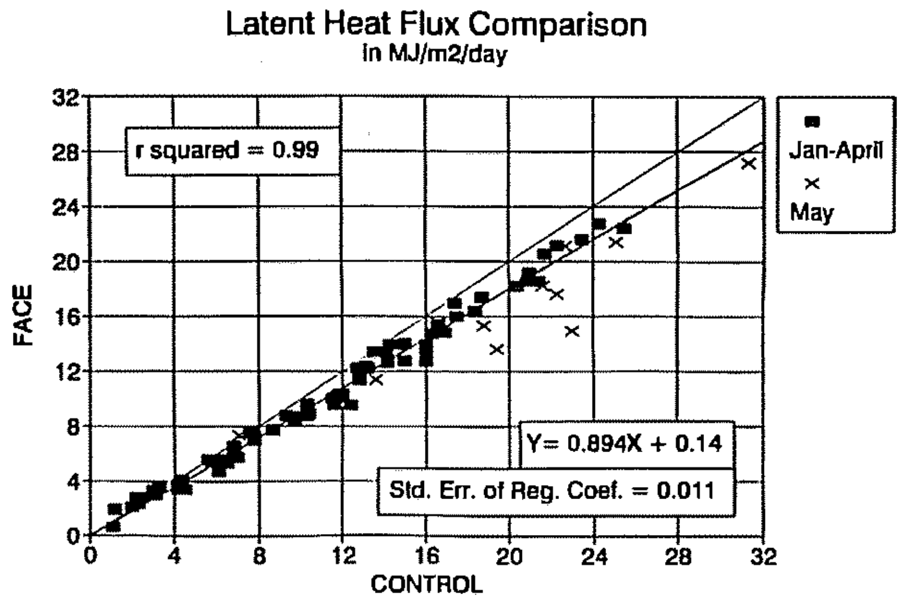


Figure 2c. Daily latent heat flux in the FACE plots versus that in the CONTROL plots for the 1992-3 FACE Wheat experiment. The regression line excludes the May data.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT ON SPRING WHEAT

P.J. Pinter, Jr., Research Biologist; B.A. Kimball, Supervisory Soil Scientist;
R.L. LaMorte, Civil Engineer; G.W. Wall, Plant Physiologist;
R.L. Garcia, Plant Physiologist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: Anticipated changes in global climate and atmospheric carbon dioxide (CO_2) concentrations have very important, albeit poorly understood, consequences for production agriculture and the world's food supply. Despite a large body of research evidence showing positive effects of CO_2 on plant growth when nutrients are not limiting, few studies have been conducted under natural field conditions without the use of chambers. Beginning in 1989 and continuing for 3 years, we studied cotton in a Free Air Carbon dioxide Enrichment (FACE) system. During the 1992-1993 season, spring wheat was exposed in the FACE facility. This is the first report of response of wheat to elevated levels of CO_2 in a realistic, open field, production environment.

APPROACH: Observations of wheat development, biomass, and final grain yield were made at the University of Arizona's Maricopa Agricultural Center (MAC), south of Phoenix, Arizona. Spring wheat (*Triticum aestivum* L. cv Yecora rojo) was sown in mid-December 1992 in east-west rows spaced 0.25 m apart. Cultural practices (cultivation, insect control, soil nutrient levels, etc.) were typical of those recommended by state Cooperative and University research staff. Plants were exposed to enriched (FACE, ~550 μmol mol^{-1}) and ambient (CONTROL, ~370 μmol mol^{-1}) CO_2 levels; treatments were replicated four times. Enrichment began on January 1, 1993 (50% emergence) and continued 24 hours a day until harvest in late May.

CO_2 treatment plots were split to test the effect of different irrigation amounts on wheat response to CO_2. Irrigation of the WET treatment was based on consumptive use requirements that were determined from estimates of daily potential evapotranspiration multiplied by an appropriate crop coefficient for wheat. Plants in the DRY irrigation treatment were irrigated on the same days as WET plots but received only 50% of the WET amount. Irrigation water was delivered to the plants using micro-irrigation (drip) tubing that was spaced 0.51 m apart (parallel to plant rows) and buried about 0.22 m deep. Irrigation amounts from emergence to harvest averaged 600 mm for the WET treatment, while DRY treatments received 275 mm. Rainfall during the same period was 123 mm.

Approximately 24 wheat plants were sampled from all replicates of each treatment combination at 7-10 day intervals during the season (18 sampling periods). Plant phenology of the main stem was determined according to both the Zadoks and Haun scales of development. Green leaf and green stem area was measured on a subsample of 3 median-sized plants using an optical planimeter. Numbers of stems and heads were counted. Crown, stem, green and non-green leaf, and head components of subsample and remaining (~21) plants were separated. Component biomass was measured after oven-drying at 65-70 °C. Leaf area index was computed from subsample specific leaf weight and green leaf biomass of all plants. Beginning on March 31 (about 1 week after anthesis), developing grains were separated from chaff by a combination of hand and machine threshing of heads that were pooled by subplot. Grain was oven-dried for a total of 14 days at 65-70 °C. Final grain yield was determined by harvest on May 25-27, 1993.

Data were analyzed using the ANOVA procedures of the Statistical Analysis System (SAS Institute, Inc.). A split-plot model was used which included CO_2 (main plot), replication, irrigation (split plot), and appropriate interaction terms. The CO_2 treatment effect was tested using the mean square of the CO_2 by replicate interaction as the error term; irrigation effects were tested using the residual mean square error term. Season-long data from harvests were tested using day of year (DOY) as a repeated measure in ANOVA. A logarithmic transformation was used to provide a more homogenous variance structure for some parameters (*e.g.*, biomass) which increased regularly through the season.

FINDINGS: Phenological development was accelerated by water stress and elevated CO_2 (Table 1). Plants exposed to the FACE treatment reached anthesis about 2 days earlier and maturity about one week earlier than CONTROLS. Although water stress had little effect on biomass components until late in the season, FACE increased total biomass significantly on most sampling dates (Fig. 1). Late season senescence of the leaf biomass was accelerated by water stress and elevated CO_2. A CO_2 factor (FACE response minus CONTROL response divided by the CONTROL response) for biomass increased gradually during the season, reaching a peak around DOY 97 in the WET treatment and about one week later in the DRY (Fig. 2). Then, as leaf senescence was accelerated in CO_2-enriched canopies, biomass in CONTROL treatments increased relative to the FACE treatments which caused the CO_2 factor for biomass to decline in both water treatments. These data support a hypothesis that the determinate growth patterns of wheat render it sink limited when exposed to supra-ambient CO_2 levels.

Elevated CO_2 resulted in a 21% increase in final yield for the DRY irrigation treatment (Table 2). Increase in yield due to CO_2 in the WET irrigation treatment was 8%. ANOVA revealed a significant interaction ($P=0.015$) between CO_2 and irrigation treatments, precluding simple separation of treatment means. Highly significant ($P \leq 0.01$) differences were found between final yields of FACE DRY and CONTROL DRY treatments. However, yields from FACE WET and CONTROL WET were only significant at a probability level of $P \leq 0.10$. Components contributing to final yield for each of the treatment combinations also were examined (Fig. 3). Some of the difference between treatments on a given day was caused by differences in developmental rates. The number of stems per plant was lower for the CONTROL WET than the other treatments, but that treatment also had the lowest tiller abortion rate. Differences between CO_2 treatments in number of heads per plant were minimal under the WET irrigation treatment, but CONTROL DRY plants developed one less head per plant than the CONTROL WET. FACE DRY produced significantly more kernels per head than any of the other treatments, perhaps because anthesis occurred several days earlier under slightly more favorable conditions. Kernel size was typically different among treatments while grains were filling but tended to converge at the end of the season.

INTERPRETATION: Analysis of the 1993 wheat growth data is continuing. Preliminary results suggest that response of Yecora rojo wheat to elevated concentrations of CO_2 is much lower than the response we observed for upland cotton grown under similar CO_2 treatments in the FACE facility. When water was not-limiting, end-of-season wheat biomass and grain yields were increased by less than 10%, considerably less than the 30-40% increase observed for cotton. Mid-season green leaf biomass and leaf area index values of wheat were increased only about 10-15% under CO_2 enrichment. In contrast, early to mid-season leaf area index of cotton was 15-40% higher with FACE. Several tentative hypotheses have been proposed for these differences. Wheat is a cool season, annual plant with relatively determinate growth and yield characteristics. Early-season CO_2 response of spring wheat may be limited by cool temperatures. Determinate growth patterns may result in a late-season sink limitation which prevents full utilization of additional CO_2 as temperatures rise during the spring. The warm season, perennial, non-determinate fruiting patterns of cotton may enable it to exploit more fully the advantage of elevated CO_2 levels.

FUTURE PLANS: An identical experiment using wheat in the FACE system is planned for the 1993-1994 growing season. Sampling routines will be expanded to acquire more detailed data on stages of plant development. Interactions between levels of CO_2 and nitrogen will be examined in subsequent years.

COOPERATORS: Alberto Giuntoli and Franco Miglietta, IATA, CNR, Florence, Italy. We gratefully acknowledge the technical assistance of C. O'Brien, R. Osterlund, L. Smith, S. Smith, R. Rokey, R. Seay, and M. Gerle and the engineering expertise of Keith Lewin, John Nagy, and George Hendrey, Brookhaven National Laboratory. Gary Richardson, ARS biometrician, provided valuable assistance in statistical analysis of the data. This research was partially supported by the Carbon Dioxide Research Program of the Environmental Sciences Division, U.S. Department of Energy.

Table 1. *Phenological development of spring wheat, T. aestivum* L. cv Yecora rojo during the 1992-93 FACE experiment. Data represent starting day of year for growth stages according to the Zadoks scale of wheat plant development.

Zadoks Growth Stage		Experimental Treatments			
Description	Code	CD	CW	FD	FW
Seedling Growth	10-19	1	1	1	1
Tillering	20-29	19.5	19.5	19.5	19.5
Stem Elongation	30-39	45	45	44	45
Booting	40-49	69	69	68	68
Inflorescence Emergence	50-59	75	76.5	73.5	73.5
Anthesis	60-69	81	83	79	80.5
Milk Development	70-97	88.5	89.5	87	88
Dough Development	80-89	95.5	97	95	95
Ripening	90-92	127	134	125	127
Maturity	92	130.5	137.5	130	131

Table 2. Final grain yields (g m^{-2}, dry weight) of spring wheat, *T. aestivum* L. cv Yecora rojo during the 1992-93 FACE experiment. Data are means ($\pm$ 1 SE) of 4 replicated subplots of each treatment combination. The area used for final yield estimates was approximately 3.3 m by 6.3 m (25, 3.3 m long plant rows). Means followed by the same letter were not significantly different at $P \leq 0.05$ (LSD=79.8 g m^{-2}).

	DRY	WET	DRY/WET
CONTROL	596 $\pm$ 5.0 a	837 $\pm$ 21.2 c	0.712
FACE	720 $\pm$ 29.8 b	904 $\pm$ 28.1 c	0.796
FACE/CONTROL	1.208	1.080	

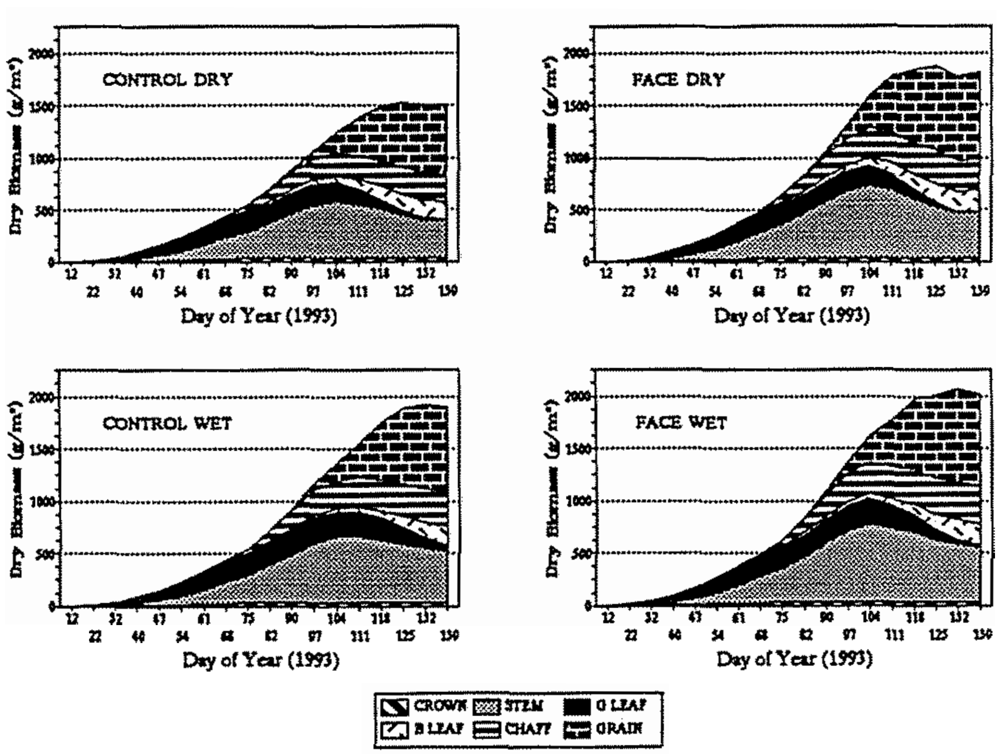


Figure 1. Seasonal trajectories of dry biomass accumulation in spring wheat, *Triticum aestivum* L. cv Yecora rojo grown in the FACE experiment of 1992-1993. Data are for six plant components: 1) Crown, including the portion of the stem which is below the ground surface; 2) Stem, above-ground culm including the attached leaf sheaths; 3) Green leaf blade tissue; 4) B Leaf, non-green leaf tissue; 5) Chaff, non-grain head tissue; and 6) Grain. These data were smoothed by a 3-term running average. DOY refers to day of year that samples were taken.

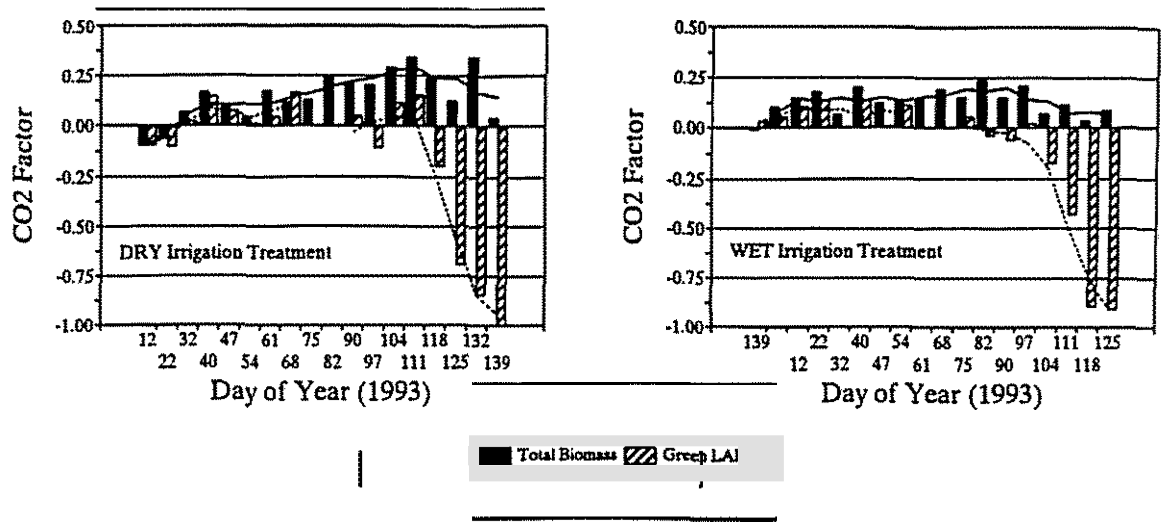


Figure 2. CO_2 enhancement factor showing relative CO_2 effects on plant biomass and green leaf area index as a function of day of year (DOY). The factor is calculated as the FACE response minus CONTROL response divided by the CONTROL response. In this figure the actual data are shown by bars; lines show a 3-term running average.

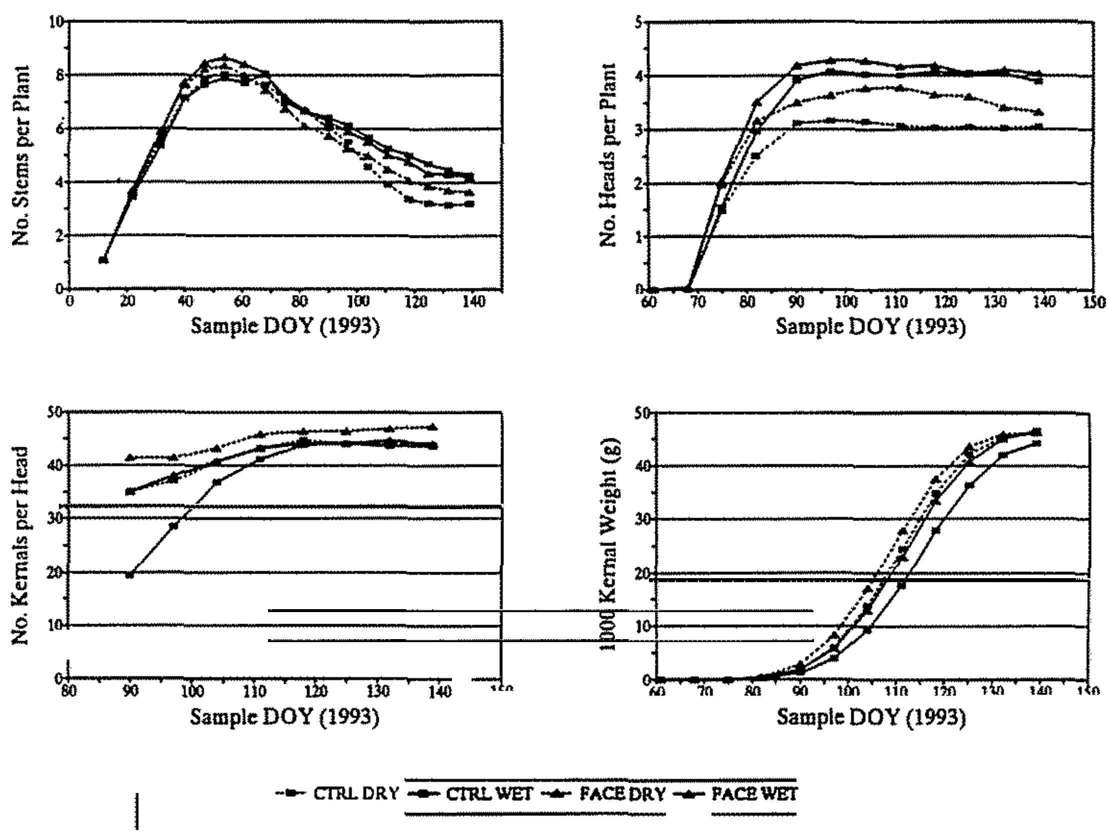


Figure 3. Components contributing to final yield for each of the treatment combinations. Plant density at time of harvest was 108.8 plants m^{-2}. Kernel mass on a dry weight basis.

PROGRESS AND PLANS FOR THE FREE-AIR CO_2 ENRICHMENT (FACE) PROJECT

B.A. Kimball, Supervisory Soil Scientist; P.J. Pinter, Jr., Research Biologist;
G.W. Wall, Plant Physiologist; R.L. Garcia, Plant Physiologist;
R.L. LaMorte, Civil Engineer; D.J. Hunsaker, Agricultural Engineer;
and F.S. Nakayama, Research Chemist

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in CO_2 concentration and any concomitant climate change on the future productivity, physiology, and water use of crops.

APPROACH: Numerous CO_2 enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30% on the average with a projected doubling of the atmospheric CO_2 concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach whose realism is unquestioned and which can produce an environment as representative of future fields as possible today is the free-air CO_2 enrichment (FACE) approach.

The FACE approach has been criticized because the prodigious quantities of CO_2 required make it expensive. A FACE experiment is expensive, but because of the relatively large area of the FACE plots, there is a huge economy of scale, with per unit of treated plant material, costing 1/4 or even less than other approaches. Thus, there is an economic incentive to have many scientists cooperate on large, comprehensive FACE experiments.

About 20 scientists from ARS, Brookhaven National Laboratory, and several universities have cooperated on a FACE project from 1989 to 1991 at the University of Arizona's Maricopa Agricultural Center (MAC). These experiments have yielded a wealth of information about the growth and physiological responses of cotton to elevated CO_2 at ample and limiting supplies of water. A 17-chapter book, "*FACE: Free-Air CO_2 Enrichment for Plant Research in the Field*," edited by G. R. Hendrey, was published in 1993 covering the FACE work up through 1989. Another 22 manuscripts covering the 1990 and 1991 cotton experiments have been written and accepted for publication in a special issue of *Agricultural and Forest Meteorology*, edited by W.A. Dugas and P.J. Pinter, Jr. (see appendix B). Data sets in IBSNAT format suitable for validation of plant growth models have been prepared.

From December 1992 through May 1993 another FACE experiment was conducted, this time on wheat at ample and limiting levels of water supply. Thirty-eight scientists from 21 different research organizations in 7 countries participated, measuring leaf area, plant height, above-ground biomass plus roots that remained when the plants were pulled, apical and morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, sap flow, root biomass from soil cores, photosynthesis, respiration, carbohydrates, photosynthetic proteins, stomatal density and anatomy, digestibility, decomposition, grain quality, soil CO_2 fluxes, and changes in soil C storage from soil and plant C isotopes. All of the data will be assembled in a standard format for validation of wheat growth models. Seven collaborating wheat growth modelers plan to utilize the data.

FINDINGS: It is beyond the scope of this report to review the results presented in the numerous above-mentioned manuscripts. Briefly, however, averaged over three years, cotton yields were increased about 40% with CO_2 concentrations elevated to 550 ppm, and there was no significant increase in water use.

Analyses of the wheat data from 1992-3 are not complete. However, the growth, morphological development, soil water balance, and energy balance aspects are reported in this volume by Pinter et al., Wall et al., Hunsaker et al., and Kimball et al. Briefly, wheat responded much differently than cotton to elevated CO_2. Early in the season in January and February when temperatures were cool, there was little response to CO_2 (concentrations of 550 μmol/mol and ambient). Then as temperatures warmed into spring, the FACE plants grew about 20% more than the CONTROL plants at ambient CO_2. The number of tillers per plant was increased from about 4 to 5. Then in May, a surprising thing happened. The FACE plants matured and senesced earlier by 7-10 days than the CONTROLs, such that the extra growing time allowed the CONTROL plants to narrow the final difference to about 8% in the well-watered plots, while the difference remained at about 20% in the water-stressed plots. The FACE plants averaged 0.6°C warmer than the CONTROLs day and night all season long in the well-watered plots, and we speculate that this temperature rise caused the earlier maturity. The energy balance and the sap flow data showed decreases in evapotranspiration of about 11% in the well-watered plots although this difference was not detected with the soil water balance measurements.

INTERPRETATION: The increasing atmospheric CO_2 concentration should be beneficial to future cotton production and probably other indeterminate crops growing in warm climates, provided water supplies do not change significantly. However, cool-season determinate crops like wheat probably will benefit also, but not as much. Irrigation requirements may be somewhat reduced for future wheat production, provided climate changes are minimal.

FUTURE PLANS: The FACE wheat experiment at ample and limited water will be replicated in 1993-4 (planting was accomplished on December 8, 1993). Funding permitting, FACE wheat experiments at ample and limiting supplies of soil nitrogen will be conduced in 1994-5 and 1995-6.

COOPERATORS: D. Clark, A. Weber, Arizona State University, Tempe, AZ; G.-Y. Nie, G. Hendrey, K. Lewin, J. Nagy, Brookhaven National Laboratory, Upton, NY; W. Hunt, S. Smith, Colorado State University, Ft. Collins, CO; A. Frumau, H. Vugts, P. Jak, Free University of Amsterdam, Amsterdam, Netherlands; H. Johnson, S. Malone, Grassland Protection Research (USDA-ARS, Temple, TX); G. Wechsung, Humbolt University, Berlin, Germany; A. Giuntoli, F. Miglietta, Inst. Environ. Anal. and Remote Sens. Agric., Florence, Italy; M. Estiarte, J. Peñuelas, Inst. de Recerca i Tecnologia Agro., Barcelona, Spain; R. Senack, J. Ham, Kansas State University, Manhattan, KS; F. Wechsung, T. Kartshall, S. Grossmann, Potsdam Inst. for Climate Impact Research, Potsdam, Germany; N. Nikolov, Rocky Mount. For. & Range Exp. Sta. (USDA-FS, Ft. Collins, CO); D. Akin, Russell Research Center (USDA-ARS, Athens, GA); R. Grant, University of Alberta, Edmonton, Alberta, Canada; R. Rauschkolb, H. Cho, S. Leavitt, University of Arizona, Maricopa and Tucson, AZ; S. Long, C. Osborne, A. Ball, University of Essex, Colchester, UK; A. Hunt, University of Guelph, Guelph, Ontario, Canada; A. Trent, L. Aiguo, University of Idaho, Moscow, ID; J. Vu, T. Sinclair, L. Allen, University of Florida (USDA-ARS, Gainesville, FL); L. Jahnke, University of New Hampshire, Durham, NH; D. Suarez, U.S. Salinity Laboratory (USDA-ARS, Riverside, CA); B. Kimball, P. Pinter, Jr., G. Wall, R. Garcia, R. LaMorte, D. Hunsaker, F. Nakayama, F. Adamsen, U.S. Water Conservation Laboratory (USDA-ARS, Phoenix, AZ); D. Hendrix, D. Akey, Western Cotton Research Laboratory (USDA-ARS, Phoenix, AZ); C. Morris, Western Wheat Quality Laboratory (USDA-ARS, Pullman, WA); J. Amthor, Woods Hole Research Center, Woods Hole, MA

GAS EXCHANGE OF SPRING WHEAT CANOPIES IN RESPONSE TO FULL-SEASON CO_2 ENRICHMENT AND DIFFERENTIAL IRRIGATION

R. L. Garcia, Plant Physiologist; G. W. Wall, Plant Physiologist; B. A. Kimball, Supervisory Soil Scientist; and P. J. Pinter, Jr., Research Biologist

PROBLEM: The biochemical-physiological basis for the direct effects of atmospheric CO_2 concentration on the carbon gain of plants is fairly well understood (Farquhar et al., 1980). This information has been utilized in some of the more recent state-of-the-art models developed to assess the effects of climate change on plant productivity (e.g., Wall et. al., 1994). Typically, these efforts have involved scaling-up from leaf level simulations to the plant community. However, Korner and Arnone (1992) have argued that scaling-up from physiological baselines to the crop or ecosystem may be an inadequate approach because of the complexity of interactions in such systems calling for whole system experimental approaches to global change research. In this study we measured gas exchange at the whole crop level. These measurements will provide us a tool for quantitative assessment of the impact of environmental changes on both short-term and long-term biological processes at the whole system level (Garcia et al., 1990).

APPROACH: The study was conducted in a rural setting about 50 km south of Phoenix, Arizona, at the Maricopa Agricultural Center of the University of Arizona. Plots of spring wheat (*Triticum aestivum* L. cv. Yecora rojo) were exposed to ambient CO_2 concentrations or to a CO_2-enriched atmosphere (about 550 umol mol^{-1}) using a Free-Air CO_2 Enrichment system. Irrigation water was applied using a subsurface drip system. The "wet" plots received enough water to match evaporative demand, whereas the "dry" plots received half the amount applied to the "wet" plots. Four steady-state canopy gas exchange systems were fabricated for continuous monitoring of carbon and water vapor exchange rates of the ambient, enriched, "wet", and "dry" treatments. After installation of the gas exchange systems in a ring, the rate of CO_2 injection into the inlet air stream was adjusted to maintain a concentration within the chamber that was near the target concentration of the ring. Net CO_2 exchange rates were measured continuously (15 minute averages) for 10 days to 2 weeks, after which the systems were moved and the plant material was harvested for leaf area and dry matter determinations. The systems were first installed in the field on February 25, 1993, and were removed on May 18, 1993.

FINDINGS: Carbon assimilation rates at the leaf and whole crop levels were greatest in the "wet" CO_2-enriched plots (Fig. 1). The "dry" CO_2-enriched plots exhibited a greater degree of enhancement over the "dry" control than the "wet" CO_2-enriched plots did over the "wet" control. Water use efficiencies were consistently highest in the "dry" CO_2-enriched plots (Fig. 2).

FUTURE PLANS: During the 1993-94 FACE experiment we intend to collect a second year of field data. We will also compare whole crop gas exchange of ambient grown wheat and barley (*Hordeum vulgare* L.).
We may also conduct a ministudy examining whole crop response to "super enrichment" at night.

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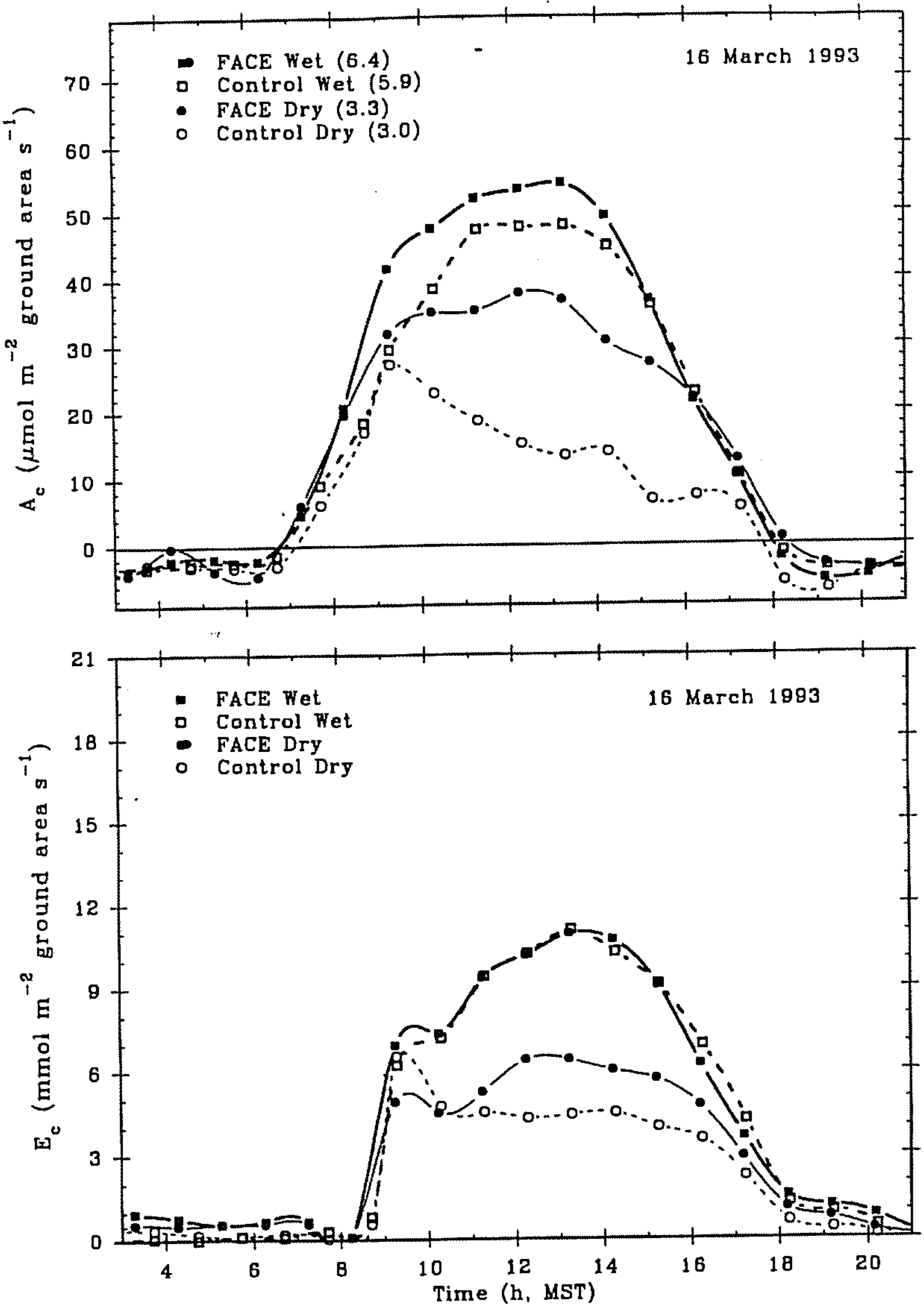

Figure 1. Diurnal courses on March 16, 1993 of net canopy CO_2 exchange rate and transpiration for spring wheat grown at atmospheric CO_2 concentrations close to 550 μmol mol^{-1} (FACE) and ambient (CONTROL).

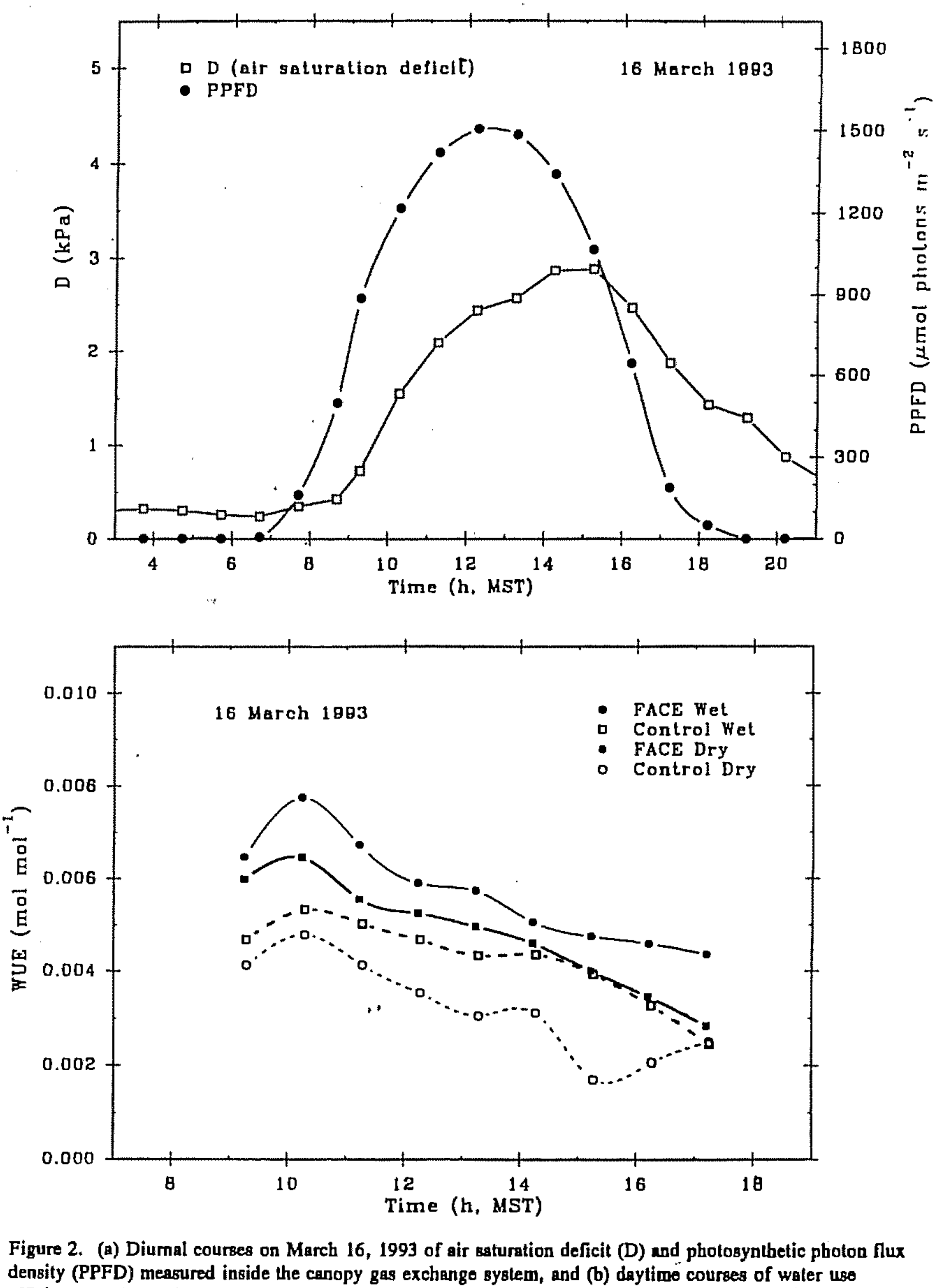

Figure 2. (a) Diurnal courses on March 16, 1993 of air saturation deficit (D) and photosynthetic photon flux density (PPFD) measured inside the canopy gas exchange system, and (b) daytime courses of water use efficiency on for spring wheat grown at atmospheric CO_2 concentrations close to 550 μmol mol^{-1} (FACE) and ambient (CONTROL).

SOIL GAS FLUXES IN CO_2-ENRICHED WHEAT

F.S. Nakayama, Research Chemist

PROBLEM: Theories have been postulated regarding the effect of an increase of CO_2 on world climate and crop production. The soil can act as a sink/source for CO_2 and, thus, can affect the overall carbon balance of the atmosphere. Soil CO_2 flux, the interchange rate of CO_2 between the soil and atmosphere, gives an indication of root and microbial activities occurring in the soil. The flux value is an important component of models depicting plant growth and overall CO_2 balance. The objective of this study is to determine the soil CO_2 flux or respiration in both natural and CO_2-enriched systems for wheat, a major economic crop of the world.

APPROACH: Soil CO_2 fluxes were determined as part of the overall Free-Air CO_2 Enrichment (FACE) experiment on wheat. Measurements were taken on the FACE experimental sites at the University of Arizona Maricopa Agriculture Center, Maricopa, Arizona. Procedures previously developed for determining flux and soil CO_2 distribution in open-top chambers were used. Gas samples were taken throughout the growing season at the surface and sub-surface locations in the different treatment combinations of CO_2 and soil moisture levels. The treatment consisted of four check and four CO_2-enriched plots. "Wet" and "dry" water levels were superimposed onto the CO_2 treatment. Four flux sampling chambers were used for each CO_2 level X water X four replicates, giving a total of 64 flux sampling sites. Treatment effects were statistically analyzed based on the split plot design. Other types of gas samples and analyses were provided to other cooperators for their work on isotopic composition of subsurface organic matter and methane and nitrous oxide fluxes.

FINDINGS: Carbon dioxide fluxes were significantly different between the CO_2-enriched and control plots and similarly with the wet and dry treatments (Table 1). No CO_2 X H_2O interaction was present. The average flux values were less than those for cotton, and an important cause would be that the wheat measurements were taken in the winter-spring period, whereas the cotton fluxes were taken in the spring-summer months.

The soil nitrous oxide (N_2O) fluxes in the order of 2 to 10 $\mu g\ m^{-2}\ h^{-1}$ are in the range of those observed elsewhere for wheat. Large variability was obtained for methane (CH_4) fluxes, although it is interpreted as being very low (Table 2). Only limited exploratory measurements were made, so no statistical analysis about treatment effects could be made for these two types of gas fluxes.

The measured soil CO_2 concentrations between those taken for the isotope and soil sampling techniques at the 30 cm depth were similar (Table 3). These observations support the assumption that the soil air removed for isotopic analysis was indeed originating from the specified soil depth and not being drawn into the sampling tubes from other locations, particularly from the soil surface, during the sampling process.

INTERPRETATION: Significantly larger soil CO_2 fluxes were present in the free-air CO_2-enriched treatments than the untreated plots for wheat. Higher irrigation levels also caused a higher flux. An interaction was absent between the CO_2 and H_2O levels. Higher fluxes would indicate higher biological activities in the soil and further meant that a greater buildup in biologically processed carbon was occurring in the CO_2-enriched than untreated system.

FUTURE PLANS: We plan to continue the soil CO_2 flux measurements in the FACE wheat study more intensively than those ran in 1993. Support also will be provided for obtaining soil CO_2 and other gas samples and gas analysis for the other modeling studies that depend upon these inputs.

COOPERATORS: S. Leavitt, The University of Arizona, Tucson, AZ; A. Mosier, USDA-ARS, Ft. Collins, CO.

Table 1. Analysis of the CO_2 enrichment and irrigation treatment effects on soil CO_2 fluxes for the January 25 - April 19, 1993.

Source	SS	df	MS	F	P
Main plots					
Blocks	47.4273	10	4.7427		
CO_2	2.75	1	2.75	11.0048	0.0062 **
Main plot error	2.31	10	0.231		
H_2O	1.1781	1	1.1781	7.5546	0.0124 *
H_2O x CO_2	0.0327	1	0.0327	0.2098	0.6518 ns
Error	3.1191	20	0.1560		
Total	56.8173	43			

Duncan's Multiple Range Test (25 Jan.- 19 Apr. 1993)

FACTOR: H_2O
Error mean square = 0.1559
Degrees of freedom = 20
Significance level = 5%
LSD, 0.05 = 0.2484

Treat.	Mean
WET	3.04 a*
DRY	2.71 b

FACTOR: CO_2
Error mean square = 0.2310
Degrees of freedom = 10
Significance level = 5%
LSD, 0.05 = 0.3229

Treat.	Mean
FACE	3.13 a*
CHECK	2.63 b

*Means followed by the same letter are not significantly different at the 0.05 probability level.

Table 2. Methane and nitrous oxide fluxes in FACE plots. (Analysis by Mosier from gas samples)

	FLUX (μg C or N m^{-2} h^{-1})			FLUX	
PLOT ID	CH_4	N_2O	PLOT ID	CH_4	N_2O
CONTROL (16 April 1993)			CONTROL (19 April 1993)		
1W1	-0.7	2.9	1W1	7.0	1.8
1W2	3.7	4.1	1W2	0.8	0.9
1W3	1.8	4.4	1W3	0.3	2.9
1W4	-2.4	8.3	1W4	-0.1	1.7
		4.9±2.3			1.8±0.8
1D1	-1.3	5.1	1D1	1.9	13.0
1D2	3.5	4.8	1D2	1.8	12.1
1D3	-4.1	9.0	1D3	-1.0	7.8
1D4	-8.5	9.6	1D4	2.1	13.9
		7.1±2.5			12.2±3.2
FACE (16 April 1993)			FACE (19 April 1993)		
2W1	0.2	3.2	2W1	0.5	1.3
2W2	-3.7	1.7	2W2	-0.04	1.8
2W3	-0.3	3.0	2W3	-1.2	0.1
2W4	-1.3	5.8	2W4	0.3	2.0
		3.4±1.7			1.3±0.9
2D1	-0.8	4.0	2D1	-9.6	4.0
2D2	-1.4	3.8	2D2	-3.4	2.8
2D3	-0.8	3.0	2D3	-0.08	1.6
2D4	-2.0	7.5	2D4	1.0	3.3
		4.6±2.0			2.9±1.0

Notes: W = wet plots
D = dry plots

Table 3. Carbon dioxide concentration in soil air and atmosphere.

Site	Depth (cm)	Soil CO_2 Conc.(%)	Atmos. CO_2 Conc.(ppm)
1	20	1.10	444
Old 1CN	30	1.12 (1.0)	
	40	1.77	
2	20	0.55	444
Old 1FN	30	1.02 (1.5)	
	40	1.23	
3	20	0.46	442
Old 2FS	30	1.46 (1.5)	
	40	1.52	
4	20	0.71	446
Old 2CS	30	1.13 (0.3)	
	40	1.49	
5	20	1.38	458
New 1CN	30	1.60 (2.0)	
	40	1.83	
6	20	1.23	669
New 1FN	30	1.53 (1.9)	
	40	1.79	

Soil-air CO_2 analysis in parenthesis run by Leavitt for the isotopic, soil carbon storage measurements.

C_3 LEAF PHYSIOLOGY MODULE IN COTCO2

G.W. Wall, Plant Physiologist; and
B.A. Kimball, Supervisory Soil Scientist

PROBLEM: Leaf physiology is central to simulating plant response to the environment. Whereas leaf temperature affects leaf physiology, leaf physiology processes, in turn, affect leaf temperature because of stomatal regulation of transpiration and, to a lesser extent, metabolic energy exchange. A CO_2 responsive cotton (*Gossypium hirsutum L.*) growth model must include a biochemical model of C_3 photosynthesis and photorespiration with CO_2 concentration and tissue temperature as an intimate component. This model of C_3 photosynthesis should be capable of calculating carbon dioxide flux, stomatal conductance, transpiration, and leaf energy balance for each unfolded leaf blade in the canopy. Estimates of whole-plant carbon and water exchange rates can be obtained by integrating CER and transpiration rates of individual leaf blades within canopy layer across all layers.

APPROACH: The *LEAF PHYSIOLOGY* module (Fig. 1) in COTCO2 (Amthor and Kimball, 1990; Wall et al., 1994) consists of three components: (1) a leaf energy balance to account for stomatal effects on leaf temperature, transpiration and assimilation; (2) a stomatal conductance model; and (3) a biochemical chloroplast CO_2 assimilation model *(Ap. 1)*.

Leaf energy balance. Components of leaf-environment energy exchange include absorbed short wave solar plus long wave sky radiation, emitted long-wave radiation, and latent, sensible, and metabolic energy exchanges *[eq. 1]*. The total absorbed radiant energy flux *(R_a)* is an input to the leaf physiology module that is calculated by the canopy model. Emitted long-wave radiation is a function of leaf temperature *[eq. 2]*. Latent heat flux is the product of the flux of water vapor onto the leaf *[eq. 3]* and the temperature dependent latent heat of vaporization *[eq. 5]*. Dew forms on the leaf when *($e_l < e_a$)*. In this case, the flux of water vapor away from the leaf is given by *[eq. 4]*. Sensible heat exchange is based on leaf and ambient air temperatures *[eq. 6]* and the whole leaf convective heat transfer in the boundary layer *[eq. 7]*. The convective heat transfer coefficient is derived from the temperature-dependent thermal conductivity coefficients of air at ambient and leaf temperatures, respectively *[eq. 8]*. Although a small component, the metabolic leaf free energy content due to carbon metabolism *[eq. 9]* is considered in the overall energy balance. The mean boundary layer thickness over one side of the leaf is a function of the characteristic dimension of that leaf and wind speed outside the boundary layer *[eq. 10]*. Boundary layer thickness is assumed to be similar over both sides of the leaf. The boundary layer conductance of water vapor diffusion for one side of the leaf is given by *[eq. 11]*. During the daytime, when stomata are open, the effective whole-leaf boundary layer resistance to water vapor diffusion for a leaf within a canopy layer is the ratio of stomata on the adaxial and abaxial leaf surfaces *[eq. 12]*. At night, when stomata are closed, whole-leaf boundary resistance is given by *[eq. 13]*. The secant method is used to solve iteratively for the leaf temperature at which the radiant energy absorbed is balanced with sensible, latent, metabolic energy exchange and long-wave radiation emitted.

Stomatal conductance. Leaf surface resistance to water vapor diffusion is the reciprocal of the sum of stomatal and cuticular conductance *[eq. 14]*. The total whole-leaf conductance of water vapor diffusion is the reciprocal of the sum of whole-leaf boundary layer resistance and whole-leaf surface resistance *[eq. 15]*. Stomatal conductance is related to mesophyll metabolism and soil water content; i.e., root signal *[eq. 16]*. Vapor pressure at the leaf surface is given by *[eq. 17]*. If photosynthesis is limited by rubisco activity *[eq. 18]* is used to calculate chloroplast ATP concentration; otherwise *[eq. 19]* is used to calculate ATP.

Whole-leaf boundary layer conductance of CO_2 diffusion is related to boundary layer resistance to water vapor *[eq. 20]*. Similarly, leaf surface conductance of CO_2, which include cuticular and stomatal conductance, is related to their respective conductances to water vapor *[eqs. 21 and 22, respectively]*. A total boundary layer plus leaf surface conductance of CO_2 is thereby defined *[eq. 23]*. An additional conductance term is derived to calculate the CO_2 partial pressure in the chloroplast; that is, the conductance of CO_2 between the intercellular spaces and chloroplast stroma *[eq. 24]*. An intercellular CO_2 partial pressure is then derived *[eq. 25]*, as is the partial pressure of CO_2 in the chloroplast stroma *[eq. 26]*.

Biochemical chloroplast CO_2 assimilation. A biochemically based C_3 photosynthetic model is employed to simulate the competitive Michaelis-Menten enzyme kinetics of ribulose bisphosphate (RuP_2) carboxylase/ oxygenase in the photosynthetic carbon reduction *(PCR)* and photorespiratory carbon oxidation *(PCO)* cycles. Based on leaf temperature, the maximum RuP_2 carboxylation and oxygenation velocities *[eqs. 27 and 28, respectively]*, the *Arrhenius-based* temperature-dependent Michaelis-Menten constants for CO_2 and O_2, the stromal CO_2 compensation partial pressure in the absence of dark respiration *[eq. 31]*, and the maximum and actual chloroplast thylakoid membrane electron transport rates are determined *[eqs. 32 and 33, respectively]*. During the daylight hours, the net carbon dioxide flux at any temperature and photon flux is a function of the partial pressure of CO_2 in the chloroplast stroma, which, in turn, is dependent on assimilation rates. For each leaf class, i.e., sunlit and shaded, a value of the partial pressure of CO_2 in the chloroplast stroma *[eq. 26]* is calculated via the secant method, which is consistent with assimilation rate for a given temperature, photon flux, and stomatal conductance. In this iterative process, the following are calculated: the RuP_2-saturated-, electron-transport-, and P_i-limited rates of carboxylation *[eqs. 34, 35 and 36, respectively]*, actual rate of carboxylation based on the minimum of the carboxylation-limited rates, and chloroplast chlorophyll ATP concentration *[eqs. 18 or 19]*. The actual net CO_2 flux *[eq. 37]*, and a new chloroplast CO_2 partial pressure, based on assimilation rate, are also computed. This procedure is repeated (secant method) until the partial pressure of CO_2 in the chloroplast is unchanged. Lastly, stomatal conductance is computed based on the new estimate of ATP concentration.

Respiration Leaf. Apparent dark respiration has two components: maintenance and growth *[eq. 38]*. Growth respiration is calculated for each leaf blade. It is based on the biochemical composition of a leaf blade and the CO_2 evolved during its production. Growth respiration is input into the C_3 leaf physiology module from the leaf growth module. Leaf maintenance respiration is calculated based on leaf blade temperature, maintenance coefficients for protein turnover and intracellular metabolite gradient maintenance, structural protein content, and leaf mass *[eq. 39]*.

FINDINGS: Diurnal output of whole-plant transpiration and carbon dioxide exchange (CER) rates for cotton (cv. Delta Pine 77) grown under ambient air and air enriched to 550 $\mu L\ L^{-1}$ CO_2 with Free-Air Carbon Dioxide-Experiment (FACE) technology during the 1991 growing season at Maricopa, Arizona, are given in Figures 2 and 3, respectively. Results were obtained from simulations performed under optimal soil moisture and nitrogen levels, so the rates reported herein represent optimum values. Trends in whole-plant transpiration and CER rates were calculated by summing the contribution of the individual leaf blades for the entire canopy. During their diurnal course, these rates follow a realistic pattern for the meteorological conditions input. For the four days reported in Figure 3, whole-plant CER were 20-25% greater during the midday peak in the 550 $\mu L\ L^{-1}$ CO_2 treatment when compared to 350 $\mu L\ L^{-1}$. In contrast, for the one day reported in Figure 2, transpiration rates were 13-18% lower in the higher CO_2 treatment.

INTERPRETATION: The basic structure of the C_3 physiology module in COTCO2 is sound and has been parameterized correctly. Realistic simulation of whole-plant CER and transpiration rates was obtained. Instability was observed in the simulated CER rates for some days, suggesting that further refinement in some parameters is required. COTCO2 has the capacity to provide quantitative estimates of global cotton production in a future higher-CO_2 world.

FUTURE PLANS: Model testing will continue to minimize the observed instability in CER. Simulations will be performed to re-parameterize those parameters that require refinement.

COOPERATORS: Dr. J.S. Amthor, The Woods Hole Research Center, Woods Hole MA.

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Appendix 1

Model of leaf physiology
(symbol definitions given in Wall et al., 1994)

Equations

Energy balance

$$0 = R_a - R_e - \lambda E - S + M \qquad [1]$$

$$R_e = 2\,\epsilon\,\sigma\,(T_{l,k})^4 \qquad [2]$$

when $(e_l \geq e_a)$

$$E = \frac{g_{t,w}(e_l - e_a)}{(P - (e_l + e_a)/2)} \qquad [3]$$

when $(e_l < e_a)$

$$E = 2\,g_{b(1),w}(e_l - e_a) \qquad [4]$$

$$\lambda = 45064 - 42.9143\,T_l \qquad [5]$$

$$S = h_c(T_l - T_a) \qquad [6]$$

$$h_c = \frac{K_{a,a} + K_{a,l}}{\delta} \qquad [7]$$

$$K_a = 0.2429 + 6.125\ (10)^{-5}\,T \qquad [8]$$

$$M = \frac{A\,\Delta G^{o'}}{6} \qquad [9]$$

Boundary layer thickness and conductance for H_2O vapor diffusion

$$\delta = 0.004\sqrt{d/v} \qquad [10]$$

$$g_{b(1),w} = \frac{D_{w,o}\,P_o\,(T_{b,k}/273.15)^{1.8}}{R\,T_{b,k}\,\delta} \qquad [11]$$

Daylight - stomates opened

$$r_{b,w} = \frac{(1+\Omega^2)/(1+\Omega)^2}{g_{b(1),w}} \qquad [12]$$

Nighttime - stomates closed

$$r_{b,w} = \frac{1}{2\,g_{b(1),w}} \qquad [13]$$

$$r_{l,w} = \frac{1}{(g_{s,w} + g_{c,w})} \qquad [14]$$

$$g_{t,w} = \frac{1}{(r_{l,w} + r_{b,w})} \qquad [15]$$

Somatal conductance for H_2O

$$g_{s,w} = \Phi\,(ATP\,e_s/e_l \qquad [16]$$

$$e_s = \frac{e_l(E + 2/r_{l,w}) - 2EP}{(2/r_{l,w} - E)} \qquad [17]$$

When photosynthesis limited by rubisco activity ($W_c \leq W_j$)

$$ATP = A_t - W_c S_p / W_j \qquad [18]$$

When photosynthesis limited by RuBP$_2$ regeneration ($W_c > W_j$)

$$ATP = \frac{(A_t - S_p)(R_p - E_p)\,W_j}{W_c R_p - W_j E_t} \qquad [19]$$

Boundary layer, cuticular, and stomatal conductance for CO_2 diffusion

$$g_{b,c} = \frac{1}{1.37\,r_{b,w}} \qquad [20]$$

$$g_{c,c} = \frac{g_{c,w}}{1.6} \qquad [21]$$

$$g_{s,c} = \frac{g_{s,w}}{1.6} \qquad [22]$$

$$g_{t,c} = \frac{1}{\frac{1}{g_{b,c}} + \frac{1}{g_{c,c} + g_{s,c}}} \qquad [23]$$

$$g_{w,c} = g_{w,c(0)}\,(1 - \frac{C_{l,s}}{C_{l,s} + W_l}) \qquad [24]$$

Leaf internal CO_2 partial pressure

$$C_i = \frac{(g_{t,c} - E/2)\,C_a - A\,P}{g_{t,c} + E/2} \qquad [25]$$

$$C_c = C_i - A\,P / g_{w,c} \qquad [26]$$

Biochemical chloroplast CO_2 assimilation

$$V_{cmax} = E_t\,chl\,A_{LEC}\,e^{(-E_{LEC}/RT_{l,k})} \qquad [27]$$

$$V_{omax} = k_c V_{cmax} \qquad [28]$$

$$K_c = A_{KC}\,e^{(-E_{KC}/RT_{l,k})} \qquad [29]$$

$$K_o = A_{KO}\,e^{(-E_{KO}/RT_{l,k})} \qquad [30]$$

$$\Gamma_* = \frac{0.5\,V_{omax} K_c O_i}{V_{cmax} K_o} \qquad [31]$$

$$J_{max} = 483\,\frac{e^{(T_{l,k}/298 - 1)E_j/RT_{l,k}}}{1 + e^{(S_j T_{l,k} - H_j)/RT_{l,k}}} \qquad [32]$$

$$\Theta J^2 - [J_{max} + I_a \frac{(1-f)}{2}]J + J_{max} I_a \frac{(1-f)}{2} = 0$$

$$W_c = \frac{V_{cmax} C_c}{C_c + K_c[1 + O_i/K_o]} \qquad [33]$$

$$W_j = \frac{J}{(4.5 + 10.5\,\Gamma_*/C_c)} \qquad [34]$$

$$W_p = \frac{V_{cmax}}{2} \qquad [35]$$

$$A = [1 - \frac{\Gamma_*}{C_c}]\,\min\{W_c, W_j, W_p\} - R_d \qquad [36]$$

[37]

Apparent dark respiration

$$R_d = R_g + R_m$$

[38]

$$R_{m,l} = \frac{R_r(T_l, T_{r,l})(m_p I_{pr} + m_l I_m)CP}{Y_{ATP}}$$

[39]

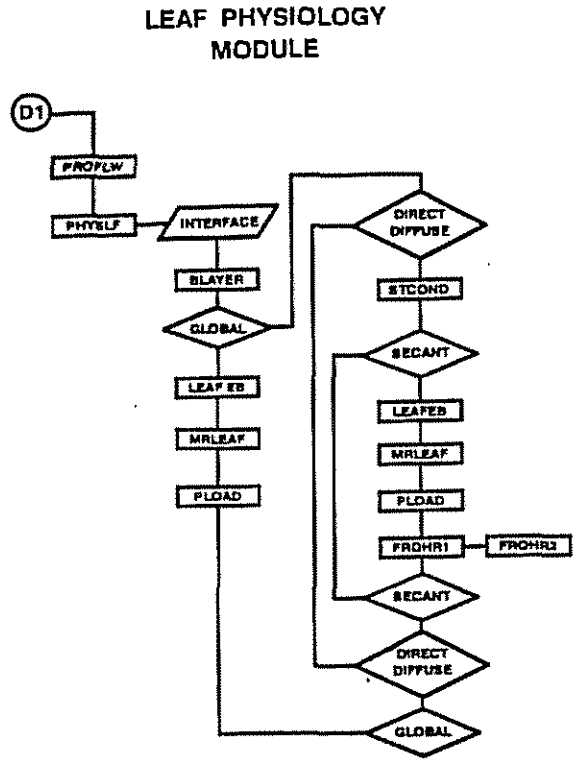

Fig. 1. Flow diagram of the *LEAF PHYSIOLOGY* module in *COTCOT2*. Subroutines include the *PROFLW* (long-wave radiation absorbed by an individual leaf blade in a canopy layer), *PHYSLF* (leaf physiology control algorithm), *BLAYER* (boundary layer), *LEAFEB* (leaf energy balance), MRLEAF (maintenance respiration of leaf blade), *PLOAD* (phloem loading of assimilates and associated respiration), *STCOND (initial guess of stomatal conductance)*, and *FRQHR1* and *FRQHR2* (biochemically based CO_2 assimilation).

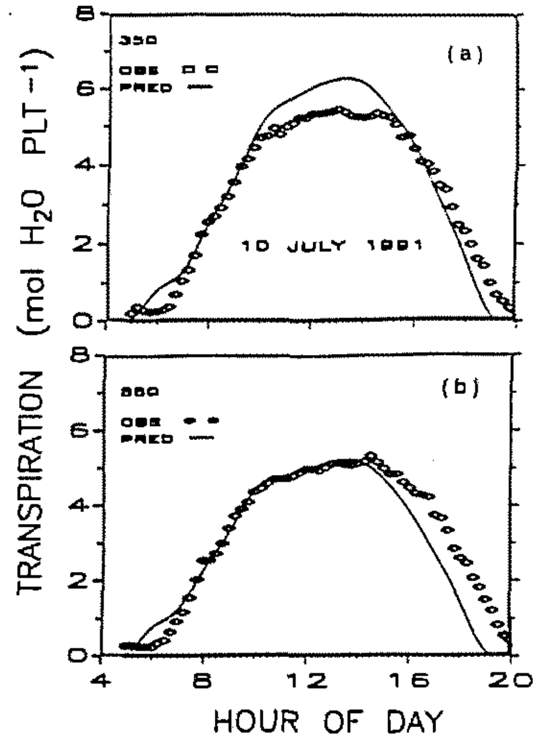

Fig. 2. Comparison of observed, e.g., stem flow gauge, (obs) to simulated (pred) diurnal trends in whole-plant transpiration rates for cotton (*Gossypium hirsutum L.* cv. Delta Pine 77) grown in ambient air (~350 µL L^{-1}) (a) and air enriched to ~550 µL L^{-1} CO_2 (b) during the 1991 FACE experiment. Simulations were performed with model generated meteorological data characteristic of Phoenix, Arizona, conditions under nonlimiting soil moisture and nitrogen levels. Simulated results, therefore, depict optimal transpiration rates.

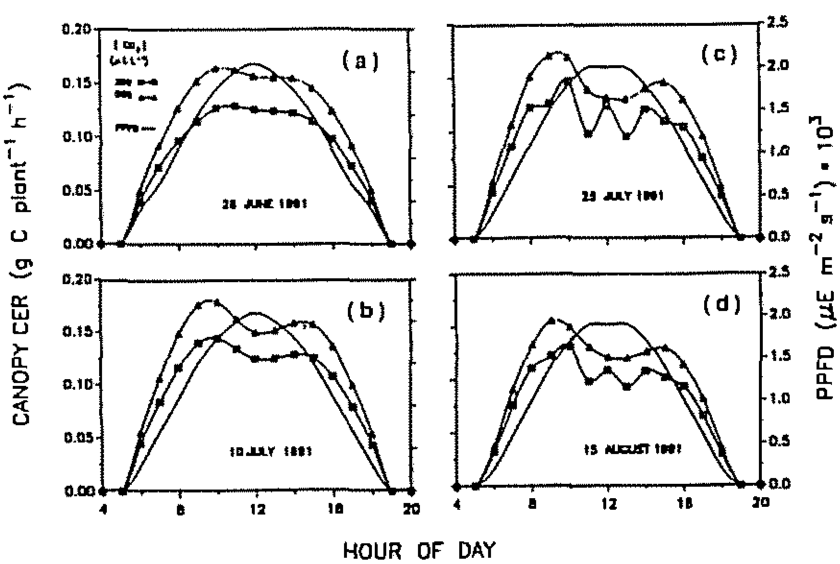

Fig. 3. Simulated diurnal trends in whole-plant gross carbon exchange rates (CER) for day of year 179 (a), 191 (b), 206 (c), and 227 (d) for cotton (*Gossypium hirsutum L.* cv. Delta Pine 77) grown under ambient air (~350 µL L^{-1}) and air enriched to ~550 µL L^{-1} CO_2 during the 1991 FACE experiment. Simulations were performed with model generated meteorological, e.g., photosynthetically active radiation (PPFD), data characteristic of Phoenix, Arizona, conditions under non-limiting soil moisture and nitrogen levels. Simulated results, therefore, depict optimal CER.

CULM DISTRIBUTION PATTERNS OF SPRING WHEAT GROWN IN A FREE-AIR-CO_2-ENRICHED ENVIRONMENT

G.W. Wall, Plant Physiologist; R. L. Garcia, Plant Physiologist;
B.A. Kimball, *Supervisory Soil Scientist*; P.J. Pinter, Jr., *Research Biologist*; and
R. L. LaMorte, Civil Engineer

PROBLEM: Culm distribution patterns of cereal grain crops follow a well defined pattern which has been quantified (Klepper et al., 1992). Plant maps have proven to be an effective methodology to characterize culm distribution patterns. The theoretical culm distribution pattern for a wheat plant, up to and including the T5 tiller, is as follows: MS, T0, T1, T2, T00, T10, T3, T01, T20, T11, T000, T4, T100, T21, T02, T30, T12, T001, T200, T101, and T5. Main stem (MS) development will occur first, followed more or less synchronously by the first true leaf tiller (T1) and the coleoptile tiller (T0). The T2 tiller will develop next, followed by the T00, etc. Formation of any culm type is highly dependent on environmental conditions. Many culm types do not develop if unfavorable environmental conditions prevail during a window of physiological time. If conditions are favorable, however, then the availability of nonstructural carbohydrates will be higher as well as the probability that a plant will initiate a particular culm type. Furthermore, the probability that the culm will produce grain is also greater. To estimate how a higher-CO_2 world will impact global wheat production, an understanding of how a wheat plant will partition its resources must be obtained. Elucidating the frequency of culm formation and their success in producing grain is essential if accurate estimates of yield potential are to be derived.

APPROACH: This field study was located at the University of Arizona Maricopa Agricultural Center in Arizona. Spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) was planted in 0.25 m row spacings at a final plant population of 130 plants m^{-2} on December 15, 1992. A Free-Air-CO_2-Enrichment (FACE) system was employed to enrich the CO_2 concentration of the ambient air ($\sim 350\ \mu L\ L^{-1}$) to a $550\ \mu L\ L^{-1}$ treatment level (main plot). A subsurface drip tape irrigation system supplied a full irrigation (100% evaporative demand) and a 50% reduction in water supply (split-plot) treatment. Plants were tagged with 36-gauge colored wire from emergence until the end of the tillering phase. A different color wire was used to identify each culm type. A record of culm types was tabulated to establish the frequency distributions.

FINDINGS: Culm distribution patterns at final harvest are reported in Figure 1. Eleven culms developed in the ambient air CO_2 treatment, whereas 13 culms were observed in the higher-CO_2 treatment. Plants grown at higher CO_2 levels developed two additional second-order culm types. Irrigation treatment enhanced the success rate of a culm once it began to develop. Six culms produced viable heads for all treatments except the full irrigation higher-CO_2 treatment, which produced seven. Therefore, the culm abortion rate was lower under the higher CO_2 full irrigation treatment.

INTERPRETATION: Plants grown in a CO_2-enriched environment under adequate soil moisture regimes produce the greatest number of culms per plant. Each culm produced had a higher level of success in producing a viable head. A one-culm difference per plant corresponds to a large potential in yield response when scaled-up to a whole-crop level.

FUTURE PLANS: During the 1993-94 FACE experiment, a second year of field data will be collected to verify trends identified during the 1992-93 season. In addition, culm distribution patterns will be quantified in a similar manner for a two-rowed malting barley (*Hordeum vulgare* L. cv. Alexis)

COOPERATORS: Dr. Frank Wechsung, Potsdam Institute for Climate Impact Research, Potsdam, Germany.

REFERENCES:

Klepper, B., Rickman, R.W. and Peterson, C.M. 1982. Quantitative characterization of vegetative development in small cereal grains. Agron. J. 74:789-792.

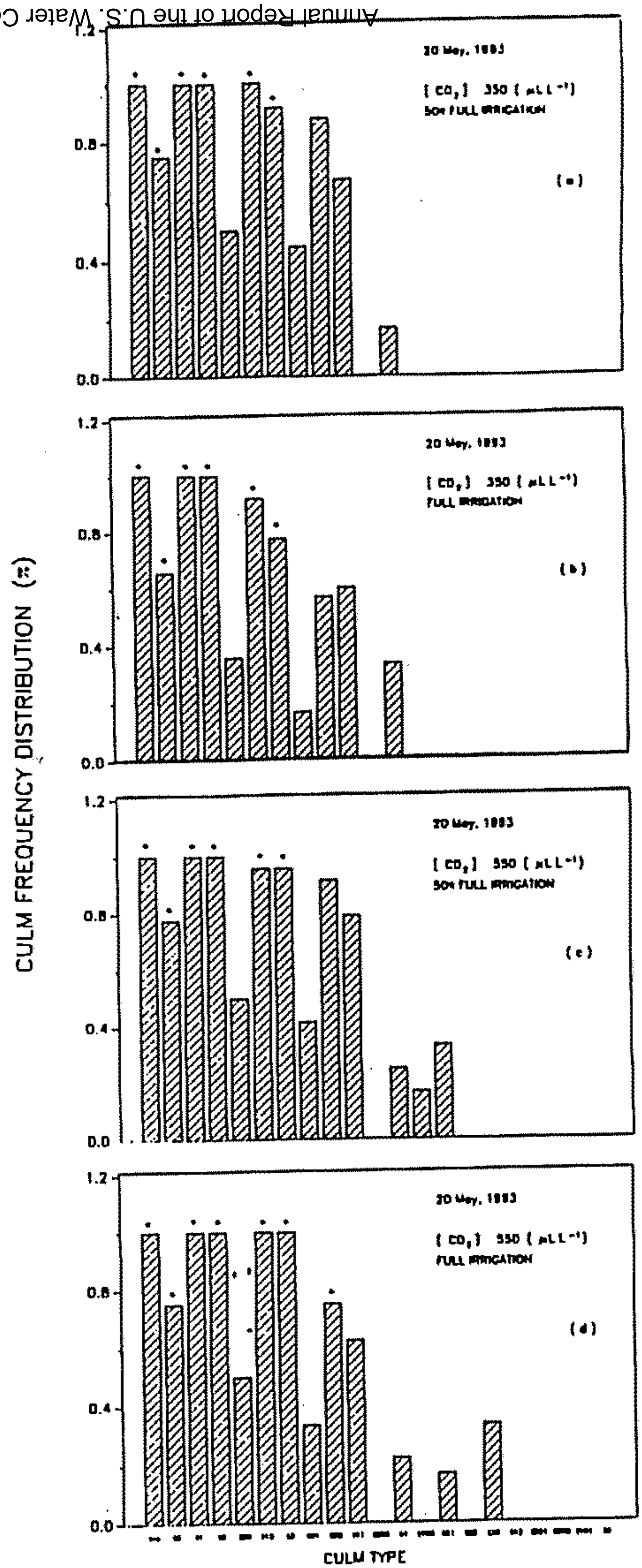

Fig. 1. Culm distribution patterns for spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) grown in ambient air ~350 $\mu L\ L^{-1}$ and air enriched to a CO_2 concentration of ~550 $\mu L\ L^{-1}$, and with full (100% of estimated evaporation) and 50% reduction in irrigation levels during the 1992-93 FACE experiment.

CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist; and B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the *most significant* ecological problem ever faced by mankind, due to the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, this belief is largely due to a lack of knowledge of the many beneficial effects of atmospheric CO_2 enrichment on Earth's plant life. Hence, it is imperative that this other aspect of atmospheric CO_2 enrichment be elucidated, so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric CO_2. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary player in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of their growth and development; and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric CO_2 enrichment, as the biological sequestering of carbon is a major factor in determining the CO_2 concentration of the atmosphere and the ultimate level to which it may rise.

APPROACH: In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment--to 300 ppm above ambient--was begun in November 1987 to two of these chambers and has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

In April 1991, eight additional open-top chambers were constructed, into each of which were planted 12 new tree seedlings, including two different species of eucalyptus (*E. microtheca* and *E. polyanthemus*), the Australian bottle tree (*Brachychiton populneum*), a conifer (*Pinus eldarica*), and more sour orange trees. Two of these chambers were maintained at the ambient CO_2 concentration, two at 150 ppm above ambient, two at 300 ppm above ambient, and two at 450 ppm above ambient for the following two years.

Numerous measurements of a number of different plant parameters have been made on the trees of both sets of chambers, some monthly, some bi-monthly, and some annually. Results of our findings are summarized below, along with results of measurements made on some other plants grown in the four large chambers beneath the sour orange trees.

FINDINGS:

(1) Idso, Kimball and Hendrix (38)* measured a number of leaf parameters on the large sour orange trees at 2-month intervals over a 2-year period, finding leaf dry weight to be unaffected by atmospheric CO_2 enrichment at a mean air temperature of approximately 4°C. At a mean air temperature of 35°C, however, individual CO_2-enriched leaves weighed up to 40% more than their ambient-treatment counterparts.

(2) Gries, Idso and Kimball (25)* measured the concentrations of 7 macro-nutrients and 5 micro-nutrients in the leaves and roots of the large sour orange trees at 2-month intervals for a period of one year, finding that atmospheric CO_2 enrichment had no major effect on nutrient concentrations in these adequately fertilized trees.

(3) Idso, Kimball, Akin and Kridler (37)* showed that for a given enhancement of the air's CO_2 content, plants whose stomatal conductances are most reduced experience the greatest increase in foliage temperature. They also showed that sour orange tree leaves are not very responsive in this regard, and that when leaf chlorophyll contents are reduced under such circumstances, leaf temperatures may actually decline.

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* For parenthetical references, see Appendix A, Manuscripts Published or Accepted in 1993.

(4) Idso and Kimball (34)* measured the photosynthetic and dark respiratory responses of three Australian tree species to atmospheric CO_2 enrichment, finding them to be comparable to the corresponding responses of sour orange trees.

(5) Graybill and Idso (24)* analyzed tree-ring records in high elevation subalpine conifers at a number of locations scattered across the southwestern United States, finding a mean growth increase of 60% or more over the past two centuries. Based upon the increase in the air's CO_2 content over that same period, this growth enhancement is exactly the magnitude of stimulation that would be expected if the conifers responded to atmospheric CO_2 enrichment as do sour orange trees.

(6) Idso, Wall and Kimball (40)* measured net photosynthetic rates of individual leaves on the large sour orange trees under ambient and CO_2-enriched conditions across a wide range of light intensities. When input to a standard canopy gas exchange model, their results led to the prediction that canopy net photosynthesis would be more than tripled by a 300 ppm rise in atmospheric CO_2 at high light intensities and that the enhancement would be even larger at low light intensities.

(7) Idso and Kimball (36)* reviewed the results of the first five years of the large sour orange tree study. The most important result identified by their review was the fact that the 2.8-fold productivity enhancement experienced over the first year and a half of the experiment, as a result of a 300 ppm increase in the air's CO_2 content, was still maintaining itself at the five-year point of the study.

(8) Idso and Kimball (35)* measured the amount of tissue regenerated from the trunk of the small sour orange trees when they were cut back five different times over the last year of the smaller chambers' two-year operation. For a 75% increase in atmospheric CO_2 from 400 to 700 ppm, aboveground regrowth biomass rose by a factor of 3.2 for these five harvests; while for a 400 to 800 ppm doubling of the air's CO_2 content, it rose by a factor of 3.9.

(9) Idso and Kimball (in preparation) measured the total amount of above ground biomass produced by the Eldarica pine trees growing within the small CO_2 enrichment chambers. At the end of two years of exposure to atmospheric CO_2 concentrations of 408, 554, 680 and 812 ppm, they found that for a 75% increase in ambient CO_2 from 400 to 700 ppm, the trees experienced a growth enhancement factor of 3.4, while for a CO_2 concentration doubling from 400 to 800 ppm, they experienced a growth enhancement factor of 4.2.

(10) Idso and Kimball (in preparation) measured total biomass production in 12 different harvests of 3 plantings of a total of 424 *Agave vilmoriniana* plants that grew in the large CO_2 enrichment chambers beneath the sour orange trees over a period of 4 years. The growth enhancement produced by a 300 ppm increase in the air's CO_2 content was found to be a linear function of mean air temperature for this desert succulent, ranging from 28% at 19°C to 51% at 29°C.

(11) Idso and Idso (33)* conducted a detailed analysis of several hundred plant carbon exchange rate and dry weight responses to atmospheric CO_2 enrichment that had been published in the scientific literature over the past ten years. They found that the percentage increase in plant growth produced by raising the air's CO_2 content was generally not reduced by less-than-optimal levels of light, water or soil nutrients, nor by high temperatures, salinity or gaseous air pollution. More often than not, in fact, the data showed the relative growth-enhancing effects of atmospberic CO_2 enrichment to be greatest when resource limitations and environmental stresses were most severe.

INTERPRETATION: The implications of our findings have a direct bearing on the current debate over anthropogenic CO_2 emissions. They clearly demonstrate that CO_2 is a very effective aerial fertilizer, enhancing plant growth under nearly all conditions.

FUTURE PLANS: We anticipate continuing the sour orange tree experiment for several more years, focusing on the effects of atmospheric CO_2 enrichment on fruit production. We also plan to study CO_2 effects on a number of other plants.

COOPERATORS: Institute for Biospheric Research; U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research.

WHEAT EVAPOTRANSPIRATION UNDER CO_2 ENRICHMENT AND VARIABLE SOIL MOISTURE

D.J. Hunsaker, Agricultural Engineer; B.A. Kimball, Supervisory Soil Scientist;
P.J. Pinter, Jr., Research Biologist; and R.L. LaMorte, Civil Engineer

PROBLEM: The Earth's rising atmospheric carbon dioxide (CO_2) is expected to impact agricultural production worldwide. One concern is how increased CO_2 will affect crop evapotranspiration (ET), which, in turn, will highly influence future agricultural water use and management. To date only a very few research studies have been attempted which sought to quantify the effects of elevated CO_2 on crop ET in agricultural fields.

The free-air CO_2 enrichment (FACE) experiment at The University of Arizona's Maricopa Agricultural Center (MAC) allows study of the effects of elevated CO_2 on crops cultivated in an environment representative of future agricultural fields. Neutron scattering and time-domain-reflectometry (TDR) equipment were used in the 1992-1993 FACE wheat experiment to measure soil water contents in the field. The objective of this study is to determine the ET of wheat grown in the FACE environment using a soil water balance approach. Other investigators, using an energy balance and sap flow measurements, also sought to determine ET in the same FACE experiment.

APPROACH: A FACE wheat experiment commenced in December 1992 on a 10-ha field site at MAC. On December 15 a spring wheat cultivar (Yecora rojo) was planted in rows spaced 0.25 m apart. The FACE technique was used to enrich four circular plots, 25 m in diameter, to a CO_2 concentration of 550 μmol mol^{-1} (FACE plots). Four matching CONTROL plots, with no CO_2 enrichment, also were installed in the field. Other details on the FACE system are provided in the 1992 USWCL Annual Report.

The FACE experimental design was a split plot with CO_2 the main effect, replicated four times. The eight circular plots were split into two semicircular subplots with each subplot receiving either a well-watered or water-limited irrigation treatment, designated Wet and Dry, respectively. A subsurface drip irrigation system was installed 0.18-0.25 m below the soil surface with 0.5-m spacings between drip tubes. About 320 mm of irrigation water was given from December 24-28 to moisten the seed bed adequately.

Seasonal irrigation scheduling was based on the soil water balance method using AZSCHED, a computer model developed by The University of Arizona, Agriculture and Biosystems Engineering Department AZSCHED estimates water requirements using the Modified-Penman method for grass-reference-crop ET combined with a crop coefficient for wheat. Irrigation of the Wet treatment was given when AZSCHED predicted the soil water of the root zone had reached a 30% depletion level. The Dry treatment was irrigated on the same day as the Wet but with 50% of the Wet amount.

Soil water contents were measured in all subplots on 38 days between December 18, 1992, and May 21, 1993. TDR equipment was used to measure soil water content in the top 0.3-m soil profile. Subsurface soil water content (from 0.3 m to 2.1 m) was measured with a neutron scattering device in 0.2-m increments. From the metered amount of irrigation water applied, rainfall amounts, and changes in soil water content, daily ET was calculated as a residual from the soil water balance.

FINDINGS: All treatments had ample soil water through February 1993 (Fig.1), because of unusually frequent and intense rainfall events in early winter. It was decided to withhold irrigation from the Dry treatment until mid-March 1993, thereby inducing some degree of water-stress compared to the Wet treatment. Soil water content differences between Wet and Dry treatments were observed between mid-March through mid-May. Soil water content for CONTROL-Wet (CW) and FACE-Wet (FW) were very similar over the entire season, while soil water content of the CONTROL-Dry (CD) was slightly higher than that of the FACE-Dry (FD) during the season. Water applied from seasonal irrigation (i.e., excluding the initial 320 mm given for crop establishment) totaled 600 and 275 mm for the Wet and Dry treatments, respectively.

Figure 2 shows the daily rate curves, and Figure 3 shows the cumulative curves of ET as calculated by the soil water balance for all treatments. Statistically significant effects ($p<0.05$) of CO_2 enrichment on ET were not detected. Although daily ET was between 17 to 50% greater for the FACE-Dry treatment compared to the CONTROL-Dry during April (Fig. 2), differences in cumulative seasonal ET were small (Fig. 3). Total seasonal ET of the Wet treatment (~575 mm) was significantly larger ($p<0.05$) than total seasonal ET of the Dry treatment (~410 mm).

INTERPRETATION: Under both well-watered and limited-water irrigation managements, elevated CO_2 concentration appears to have very little effect on wheat evapotranspiration as determined by the soil water balance. This result was the same as that determined in the FACE cotton experiments of 1990 and 1991 using similar procedures.

FUTURE PLANS: A second FACE wheat experiment is planned for the 1993-1994 season. ET will again be determined from soil water balance measurements.

COOPERATORS: See FACE cooperator listing in the *1993 USWCL Annual Report* entitled "Effects of free-air CO_2 enrichment (FACE) on the energy balance and evapotranspiration of wheat," by B.A. Kimball.

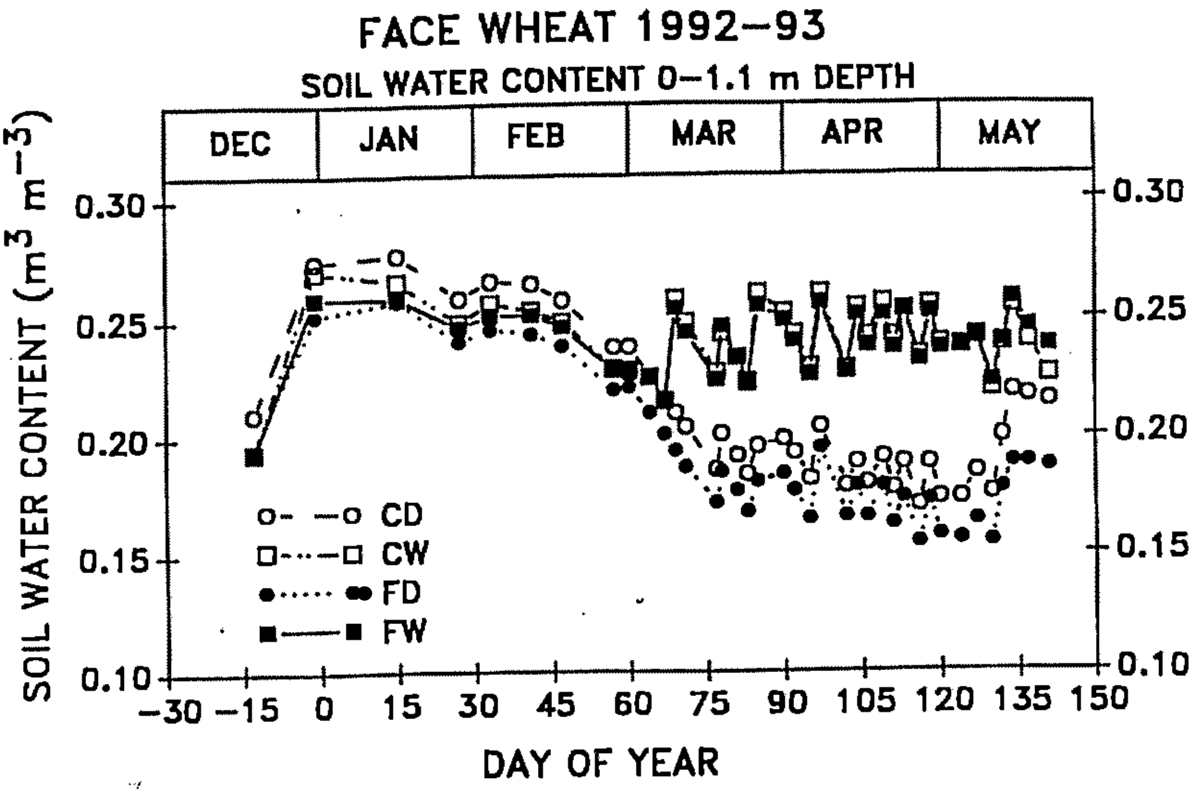

Figure 1. Soil water contents (0-1.1-m soil profile) with day-of-year for Control-Day (CD), Control Wet (CW), FACE-Day (FD), and FACE-Wet (FW) treatments. The values are averages of the four replicates.

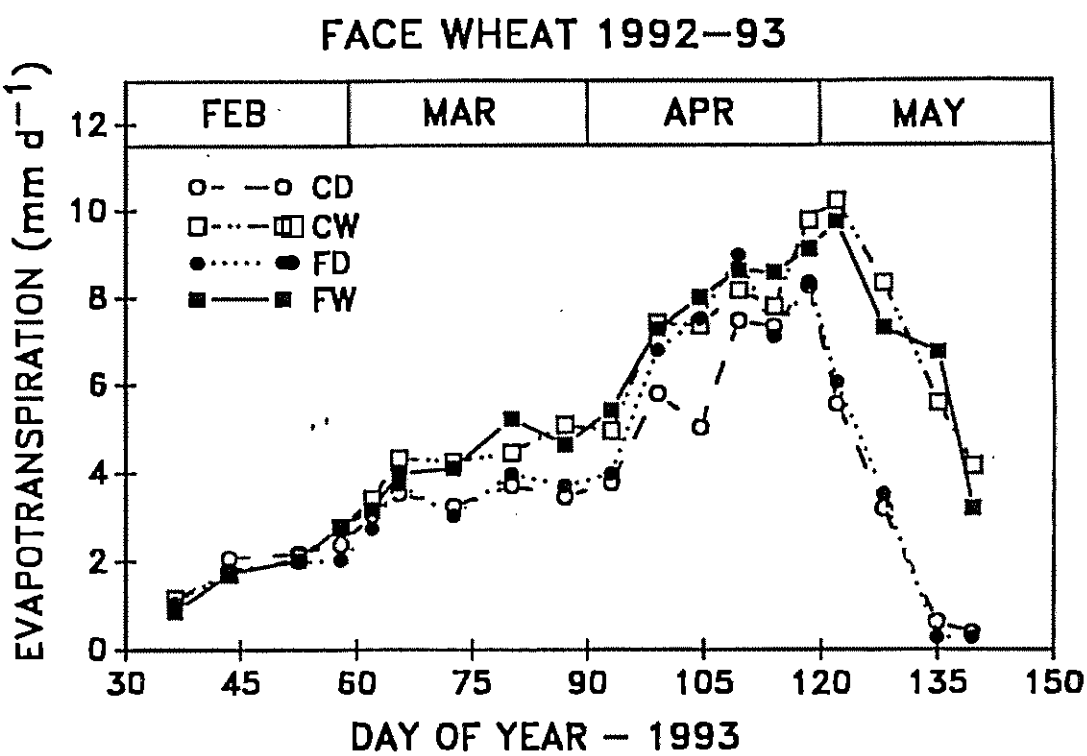

Figure 2. Soil water balance estimates of daily evapotranspiration for the CD, CW, FD, and FW treatments. The values are averages of the four replicates.

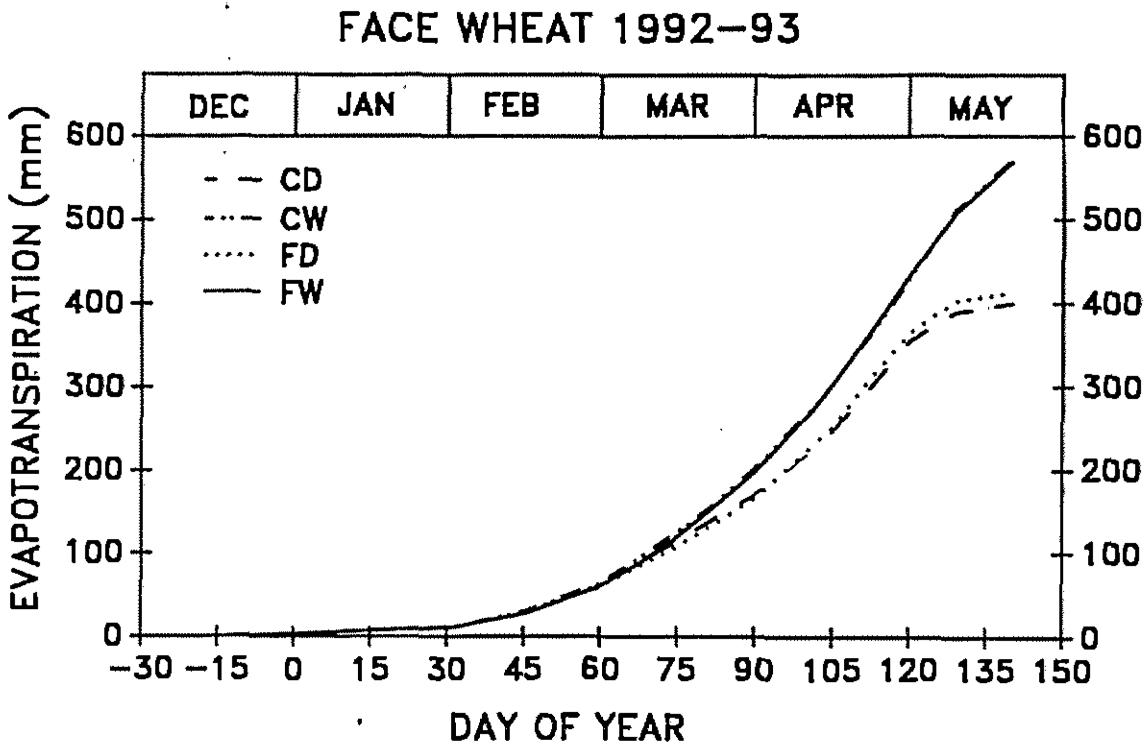

Figure 3. Cumulative evapotranspiration with day-of-year for the CD, CW, FD, and FW treatments. The lines are averages of the four replicates.

ESTIMATING CROP WATER DEFICIT USING THE RELATION BETWEEN SURFACE-AIR TEMPERATURE AND SPECTRAL VEGETATION INDEX

M.S. Moran, Physical Scientist; and T.R. Clarke, Physical Scientist

PROBLEM: One of the most popular algorithms using optical remote sensing for farm management is the Crop Water Stress Index (CWSI), which correlates crop water stress with the foliage-air temperature difference. Jackson et al. (1981) utilized physical energy balance equations to define CWSI as a function of the ratio of transpiration Γ to potential evapotranspiration $E\Gamma_p$, where CWSI=0.0 for well-watered conditions and CWSI=1.0 for maximum stress conditions. To compute CWSI, it is necessary to have measurements of foliage temperature T_c (C°), air temperature T_a (°C), net radiant heat flux density R_n (W m^{-2}), and vapor pressure deficit (VPD) of the air (kPa). It also is necessary to make an estimate of aerodynamic resistance (r_a) of the canopy to sensible heat transfer (s m^{-1}). Because of the difficulty of measuring T_c and r_a for partial crop conditions, application of CWSI is generally restricted to mature, full-canopy crops. This restriction limits the usefulness of CWSI because many farm management decisions are most crucial for partial-cover crops in the early stages of development. In response to this, a new index, termed Water Deficit Index (WDI), was developed based on combination of a spectral vegetation index with surface temperature measurements (a composite of both the soil and plant temperatures) to determine field water deficit conditions for partial-cover crops (Moran et al., 1993).

APPROACH: WDI utilizes physical energy balance equations to define the four vertices of a trapezoidal shape (termed Vegetation Index/Temperature [VIT] Trapezoid) in a plot of surface-air temperature (T_s-T_a) versus SAVI** that encompasses all possible combinations of SAVI and T_s-T_a for one crop type on one day (Fig. 1). That is, for full-cover, well-watered vegetation,

$$(T_s-T_a)_1=[r_a(R_n-G)/C_v][\gamma(1+r_{cp}/r_a)/\{\Delta+\gamma(1+r_{cp}/r_a)\}]-[VPD/\{\Delta+\gamma(1+r_{cp}/r_a)\}], \quad (1)$$

where the subscript n of $(T_s-T_a)_n$ refers to vertex n in Figure 1, G is the soil heat flux density (W/m^2), r_{cp} is the canopy resistance at potential evapotranspiration (s m^{-1}), C_v is the volumetric heat capacity of air (J °C^{-1} m^{-3}), γ the psychrometric constant (kPa °C^{-1}), Δ the slope of the saturated vapor pressure-temperature relation (kPa °C^{-1}). For full-cover vegetation with no available water,

$$(T_s-T_a)_2=[r_a(R_n-G)/C_v][\gamma(1+r_{cx}/r_a)/\{\Delta+\gamma(1+r_{cx}/r_a)\}]-[VPD/\{\Delta+\gamma(1+r_{cx}/r_a)\}], \quad (2)$$

where r_{cx} is the canopy resistance associated with nearly complete stomatal closure. For saturated bare soil, where r_c=0 (the case of a free water surface),

$$(T_s-T_a)_3=[r_a(R_n-G)/C_v][\gamma/(\Delta+\gamma)]-[VPD/(\Delta+\gamma)], \quad (3)$$

and for dry bare soil, where $r_c=\infty$ (analogous to complete stomatal closure),

$$(T_s-T_a)_4=[r_a(R_n-G)/C_v]. \quad (4)$$

Referring to Figure 1 and assuming that the measurements of T_s-T_a and SAVI cross at point C, the WDI is the distance AC divided by the total distance AB. Thus, WDI=0.0 for well-watered conditions and WDI=1.0 for maximum stress conditions. The WDI is operationally equivalent to the CWSI for full-cover canopies where a measurement of surface temperature (T_s) is equivalent to a measurement of foliage temperature (T_c).

The on-site measurements necessary to solve Eqs. (1)-(4) and compute WDI are simply R_n, VPD, T_a and wind speed. A value of G can be estimated as a function of R_n and percent crop cover (or SAVI) (Clothier et al., 1987). It also is necessary to know the crop type and to estimate maximum and minimum possible stomatal resistances (r_{cx} and r_{cp}). In many cases, these inputs are known or can be reasonably estimated.

** The spectral vegetation index used in this analysis was the Soil-Adjusted Vegetation Index (SAVI), where SAVI = $(\rho_{NIR}-\rho_{red})/(\rho_{NIR}+\rho_{red}+L)(1+L)$, and ρ_{NIR} and ρ_{red} are the near-IR and red reflectances, respectively, and L is assumed to be 0.5 for a wide variety of LAI values (Huete, 1988). SAVI has been found to be linearly correlated with percent vegetation cover.

FINDINGS: This new index, WDI, was evaluated as a tool for irrigation management using aircraft-based measurements of T_s and SAVI of an alfalfa field at the Maricopa Agricultural Center (MAC), located 40 km south of Phoenix, Arizona. The aircraft was flown at 100 m above ground level along transects through each field, and all the instruments were calibrated and pointed normal to the surface. Data for one harvest cycle and two sites (A and B) were processed for analysis (Figure 2).

A comparison of the T_s-T_a and SAVI data for the two sites within the alfalfa over the harvest period illustrates the sensitivity of these measurements to irrigation practices and vegetation growth (Figs. 3a and 3b). Theoretically, for a constant SAVI value, the proximity of any point to the left or right limits of the trapezoid would indicate more or less available water, respectively. On day of year (DOY) 213, the SAVI and T_s-T_a of sites A and B were very similar. On DOY 229, site B was irrigated and site A was not. This resulted in a shift of site B data upward and to the left within the trapezoid, indicating a slight increase in vegetation and substantial decrease in T_s-T_a from DOY 213. Site A was irrigated with the same amount of water several days later. However, it is apparent that the surface temperature of site A remained higher (and the SAVI remained lower) than that of site B for the next two weeks. This lag could be an indication of lower plant biomass due to the late irrigation. Finally, by DOY 271 the two sites within the field had nearly identical SAVI and T_s-T_a values. This could indicate that the crop at site A was able to recover later in the harvest cycle.

Computations of WDI for sites A and B of the alfalfa field reflects the result of differing irrigation practices (Fig. 4). WDI of site A was nearly equal to 1.0 on DOY 229, just prior to irrigation; whereas, the recent irrigation of site B on the same day resulted in a WDI value close to zero. The resultant lag in the vitality of the crop at site A also was apparent in the values of WDI. However, the two sites had nearly identical WDI at the end of the growing season. Unfortunately, we can't quantify the differences in crop stress for these two sites because leaf turgor and soil moisture measurements were not made during this experiment.

INTERPRETATION: The Water Deficit Index (WDI) is based on the use of spectral sensors to detect crop water deficit. The remotely-sensed measurements of surface reflectance and temperature required for computation of WDI are currently available with ground-, aircraft-, and satellite-based sensors. Thus, without any further technological developments, it is possible to compute WDI for many farm and resource management applications at local and regional scales. WDI has potential for such farm managements applications as irrigation scheduling, predicting crop yields, and detecting certain plant diseases. Other resource management applications could include drought prediction, crop damage assessment, and monitoring regional land cover changes.

FUTURE PLANS: The next step in this analysis is to determine the sensitivity of the WDI algorithm to the accuracy of the input values. We also plan to determine threshold values of WDI for use in irrigation scheduling.

COOPERATORS: Alain Vidal, CEMAGREF-ENGREF Remote Sensing Laboratory, 34033 Montpellier, FRANCE; Yoshio Inoue, NIAES, Laboratory of Agro-Biological Measurements, Tsukuba, JAPAN; Ray Jackson, Retired, USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona USA.

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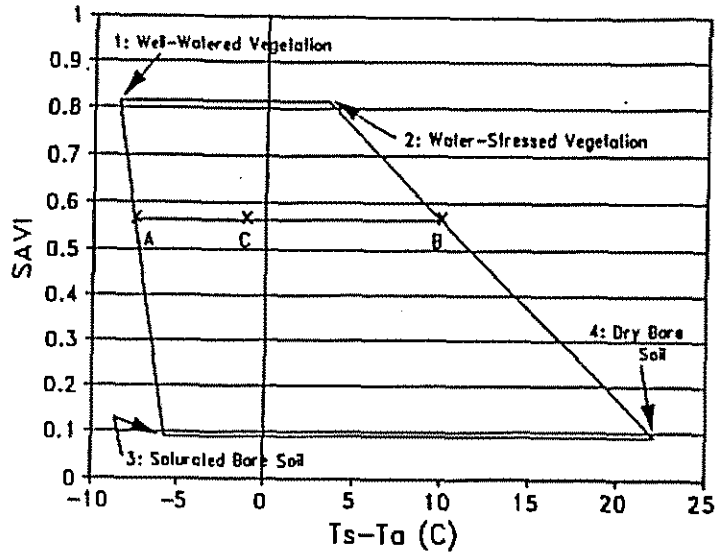

Figure 1. The trapezoidal shape that would result from the relation between (T_s-T_a) and the soil-adjusted vegetation index (SAVI). The *Water Deficit Index* (WDI) for C is equal to the ratio of distances AC and AB.

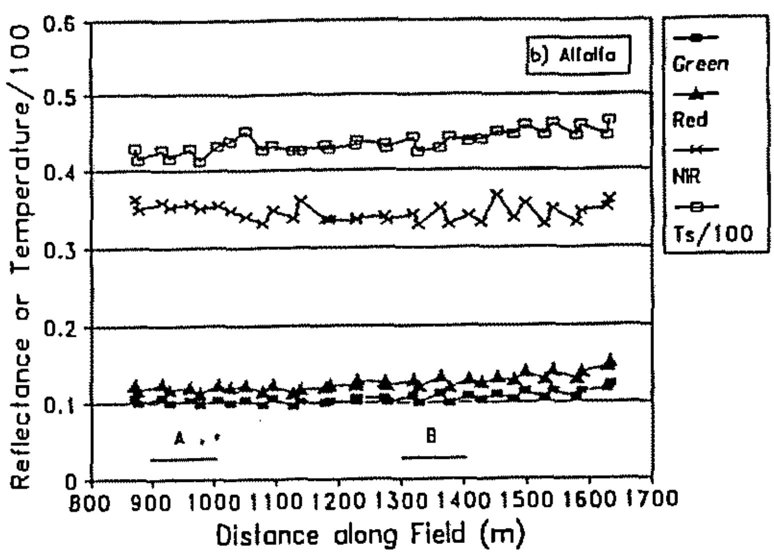

Figure 2. Aircraft-based measurements of spectral reflectance and temperature (divided by 100.0) for an alfalfa field at MAC. The field was sparsely vegetated on this date. The zig-zag pattern along some of the lines is due to the fact that data from two flight lines (approx 15 min apart) were combined into the one data set presented here.

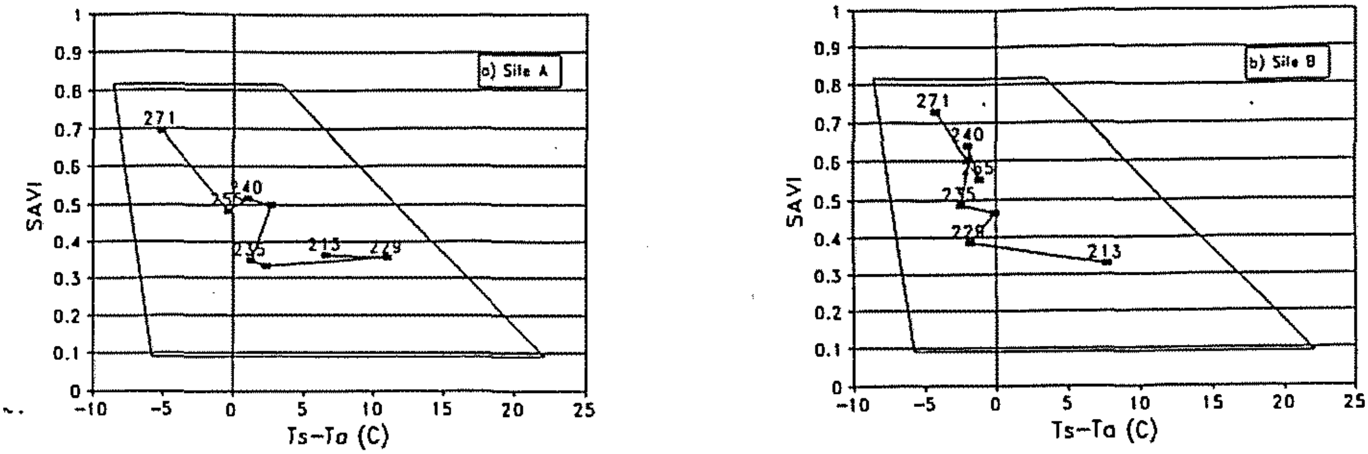

Figure 3a,3b. Values of SAVI and surface-air temperature (T_s-T_a) for sites A and B in the alfalfa field. The numbers within the graph represent the day of year (some dates are not listed for graphic clarity). Theoretically, the trapezoid vertices change each day, but for this figure, seasonal vertex locations were used.

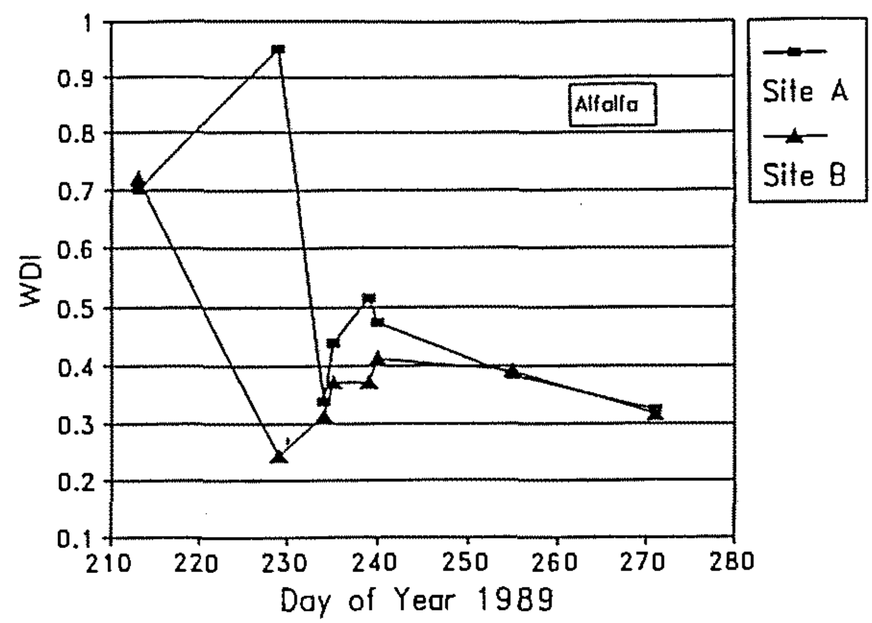

Figure 4. Values of Water Deficit Index (WDI) for a) sites A and B in the alfalfa field over a single harvest period.

ESTIMATION OF DAILY TRANSPIRATION RATE BASED ON SURFACE TEMPERATURE, SPECTRAL VEGETATION INDEX, AND BASIC METEOROLOGICAL DATA

M. S. Moran, Physical Scientist; and P. J. Pinter Jr., Research Biologist

PROBLEM: There are many proven methods for estimation of crop water loss due to evapotranspiration (the sum of evaporation from the soil and transpiration from plant leaves). However, it is essential to estimate transpiration separately from evapotranspiration for better understanding of water and energy exchange processes in the soil-plant-atmosphere continuum as well as for more efficient water use in plant production. Nevertheless, few methods are available for estimating the transpiration rates of intact plants over wide areas. Our objective, thus, was to estimate the daily transpiration rates (mm/day) of a crop over a growing season using remotely-sensed estimates of surface reflectance and temperature and readily-available meteorological data. The following approach was proposed by Dr. Yoshio Inoue, NIAES, Laboratory Agro-Biological Measurements, Tsukuba, Japan (Inoue et al., 1993).

APPROACH: The intercepted or absorbed photosynthetically active radiation (A_{par}) has been related exponentially to leaf area index (LAI) where

$$fA_{par} = A_{par}/PAR = [R_s(1-e^{(-k(LAI))})]/R_s, \tag{1}$$

and fA_{par} is the percent (%) fraction of absorbed PAR (A_{par}), R_s is the incoming solar radiation (W/m²), and k is an extinction coefficient. There is further evidence that fA_{par} can be well estimated by spectral reflectance measurements (Pinter, 1993). On the basis of these results, we can assume that $[1-e^{(-k(LAI))}]$ is a linear function of the SAVI [where SAVI = $(\rho_{NIR}-\rho_{red})/(\rho_{NIR}+\rho_{red}+L)(1+L)$ and ρ_{NIR} and ρ_{red} are the near-IR and red reflectances, respectively, and L is 0.5] and

$$fA_{par} = a+b(SAVI), \tag{2}$$

where a and b are empirically-derived coefficients.

Further, one can define the net radiation of a crop, R_{nc}, as

$$R_{nc} = R_s - R_{sc} + R_l - R_{lc}, \tag{3}$$

where R_{sc} is the solar radiation reflected by the crop (W/m²), and R_l and R_{lc} are the incoming and outgoing longwave radiation (W/m²), respectively. On a daily basis, we can assume that the crop and air temperatures would be similar and the value of $(R_l - R_{lc})$ would be negligible relative to the value of $(R_s - R_{sc})$. So, Eq. (3) can be simplified to

$$R_{ncd} = R_{sd} - R_{scd}, \tag{4}$$

where the subscript d refers to daily values in units mm/day. Assuming the value R_{scd} is equal to $(1-fA_{par})R_{sd}$, Eq. (4) can be rewritten

$$R_{ncd} = (fA_{par})R_{sd} = a'(SAVI)R_{sd}, \tag{5}$$

where a' is a constant value to be determined empirically. And, assuming that for well-watered conditions, all the PAR energy intercepted by the crop on a daily basis is utilized for transpiration, then

$$\Gamma_{pd} = R_{ncd} = a'(SAVI)R_{sd}, \tag{6}$$

where Γ_{pd} is the daily potential crop transpiration (mm/day).

Next, we can estimate "actual" daily transpiration (Γ_{ad}) by combining this concept with the Jackson-Idso Crop Water Stress Index (CWSI) (Jackson et al., 1981). The CWSI was proposed as an indicator of crop water status, and CWSI can be calculated based on canopy and air temperatures (T_c and T_a) and vapor pressure deficit (VPD). The CWSI for plants is defined theoretically as CWSI = $1-\Gamma_a/E\Gamma_p$, where $E\Gamma_p$ is the potential evapotranspiration (assumed to be equal to the potential transpiration (Γ_p)). Therefore, Γ_{ad} can finally be estimated by

$$\Gamma_{ad} = a'(SAVI)R_{sd}(1-CWSI). \tag{7}$$

FINDINGS: An initial test of the technique for estimation of daily transpiration was conducted based on an existing data set acquired in an experiment in an alfalfa field at the U.S. Water Conservation Laboratory (USWCL) in Phoenix, Arizona. In this experiment, micrometeorological data were monitored on an hourly basis and spectral and agronomic characteristics of the surface were observed on a regular basis over the growing season. Four different irrigation regimes were applied to the alfalfa: the WET treatment received two irrigations between cuttings; the EARLY treatment was irrigated once, immediately after harvest; the LATE treatment received water midway between cuttings; and the DRY treatment received no supplementary water by irrigation from one harvest until the next. This initial analysis was limited to one harvest period in 1985 from DOY 154 to 184, when reflectance and temperature measurements were made nearly every day and clear-sky conditions persisted for 28 of 30 days.

The value of a' in Eq. (7) was computed based on evaluation of the relation between SAVI (@ 1030h), R_{sd} and $E\Gamma_{sd}$ (daily $E\Gamma$ measured using a lysimeter) for full-cover, well-watered crops on clear days. Under these circumstances, we assumed that $\Gamma_{pd} = E\Gamma_{sd}$, and thus,

$$a' = E\Gamma_{sd} / (SAVI \cdot R_{sd}). \tag{8}$$

The a' value for alfalfa was computed to be 1.50.

Based on this value of a' and the CWSI, values of Γ_{sd} were computed for the WET, EARLY, LATE and DRY alfalfa plots. The values of Γ_{sd} for the EARLY and WET plots correspond as expected with the $E\Gamma_{sd}$ values measured by lysimeters in each plot (Fig. 1). That is, Γ_{sd} is substantially lower than $E\Gamma_{sd}$ when vegetation density is low (DOYs 158-170), and then Γ_{sd} is nearly equal to $E\Gamma_{sd}$ for full-cover canopy. Furthermore, the trend of decreasing $E\Gamma_{sd}$ with time in the EARLY treatment is reflected in the Γ_{sd} estimates.

Estimates of Γ_{sd} for the four treatments (WET, EARLY, LATE and DRY) also were reasonable (Fig. 2). That is, the Γ_{sd} of the WET plot remained high throughout the harvest cycle; the Γ_{sd} of the EARLY plot was similar to the WET plot early in the cycle and decreased late in the cycle; the Γ_{sd} of the LATE plots was low until the late irrigation; and the Γ_{sd} of the DRY plots remained lower than all others throughout the harvest cycle.

Considering Eq. (7), it is apparent that this approach for estimation of Γ_{sd} accounts for both differences in vegetation density and plant stress. As such, it is informative to look at both biomass and CWSI in relation to estimates of Γ_{sd}. For example, the transpiration of the WET plot was lower than that of the EARLY plot for the first half of the growth cycle and higher during the second half (Fig. 3a); yet, the biomass measurements taken in the two plots over the growth cycle were nearly identical (Fig. 3b). The differences in Γ_{sd} between the two plots were due to corresponding differences in CWSI (Fig. 3c).

INTERPRETATION: Based on these results and the sound theoretical foundation, it is likely that this approach will be successful for evaluation of daily transpiration rates of full-cover crop canopies. The most difficult aspect of the application will be computation of a'. Unfortunately, this may be both crop- and site-specific since a' is simply the slope of the fA_{PAR} and SAVI relation.

FUTURE PLANS: Because actual transpiration measurements were not made in the alfalfa experiment, the results presented here simply demonstrate (but do not validate) the technique. Further experiments in which transpiration was measured with stem-flow gauges were conducted this summer in Japan and should allow validation of this approach.

COOPERATORS: Yoshio Inoue, NIAES, Laboratory of Agro-Biological Measurements, Tsukuba, Japan

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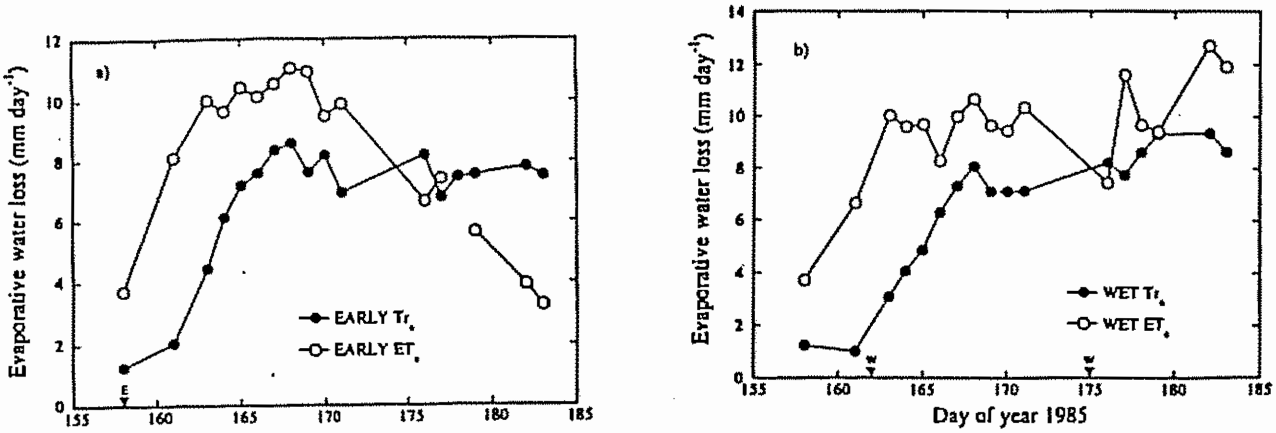

Figure 1. Comparison of estimated Γ_{ad} and measured $E\Gamma_{ad}$ for the EARLY and WET alfalfa treatment plots. Triangles along the X-axis indicate the dates of irrigation in each plot.

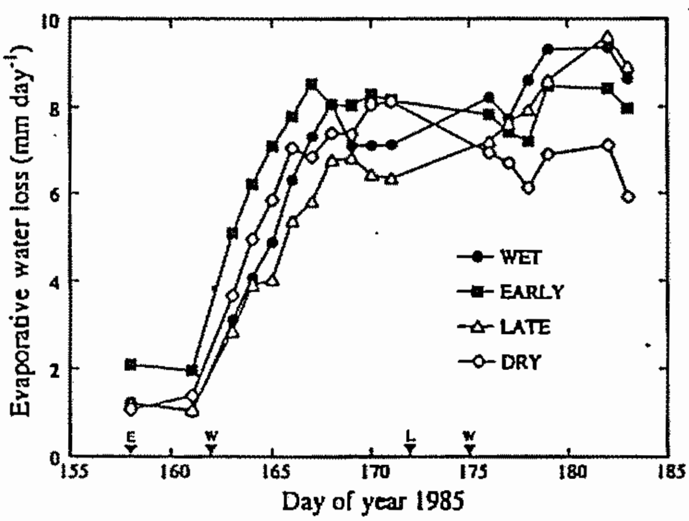

Figure 2. Comparison of estimated Γ_{ad} values for the WET, EARLY, LATE and DRY alfalfa treatment plots. Triangles along the X-axis indicate the dates of irrigation in each plot.

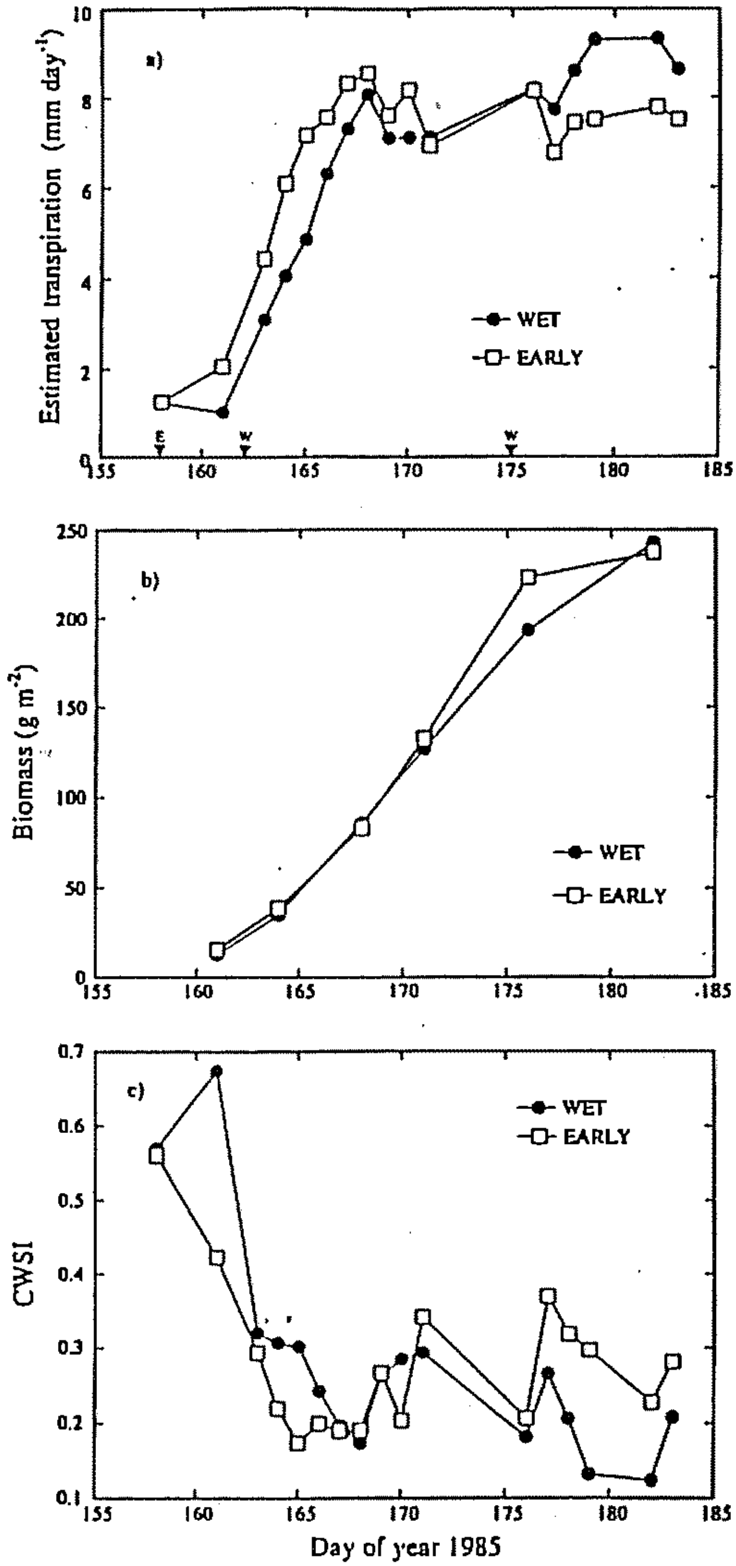

Figure 3. For a WET and EARLY treatment over a single alfalfa harvest period, a) estimates of daily transpiration (T_{ad}) and measurements of b) biomass and c) CWSI.

INTEGRATION OF REMOTE SENSING AND HYDROLOGIC MODELING THROUGH INTERDISCIPLINARY SEMI-ARID FIELD CAMPAIGNS: MONSOON'90, WALNUT GULCH'92 AND SALSA-MEX

M.S. Moran, Physical Scientist; T.R. Clarke, Physical Scientist; and
P.J. Pinter, Jr., Research Biologist

PROBLEM: Accurate characterization of the components on the hydrologic cycle and surface energy balance over a wide range of scales must be accomplished to advance our understanding and ability to model land surface and climatic interactions. This is a difficult task in any region, but the challenge is compounded in arid and semi-arid regions because of the relative extremes and large spatial and temporal gradients encountered in water and energy balance components. One means of gaining a synoptic understanding of the water and energy balance at regional scale is to conduct large-scale interdisciplinary field campaigns which combine traditional ground and atmospheric measurements with remotely sensed measurements. Two such experiments, Monsoon'90 and Walnut Gulch'92, have been conducted in a semi-arid rangeland southeast of Tucson, Arizona; and a third experiment, SALSA-MEX, has been proposed.

APPROACH: The Monsoon'90 Experiment was conducted in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW), primarily during the wet season (July/August) in 1990 (Kustas et al., 1991). A primary objective of this combined ground, aircraft, and satellite campaign was to assess the feasibility of utilizing remotely-sensed data coupled with water and energy balance modeling for large area estimates of fluxes in semi-arid rangelands. During the intensive measurement period, an interdisciplinary team of scientists made intensive measurements of meteorological, atmospheric, edaphic, and vegetative conditions simultaneously with aircraft- and satellite-based spectral measurements. Most of the ground-based measurements were focused on eight sites which covered the main vegetation biomes in the regions. At each site, there were continuous measurements of meteorological conditions at screen height, near surface soil temperature and soil moisture, surface temperature, incoming solar and net radiation, soil heat flux, and indirect determination of sensible and latent heat fluxes.

The Walnut Gulch'92 Experiment (WG'92) was conducted as a follow-up to Monsoon'90, and designed to capitalize on preliminary research results and existing hydrologic and meteorologic instrumentation at WGEW (Moran et al., 1993). WG'92 was conducted during the dry, early-monsoon, mid-monsoon, post-monsoon, and "drying" seasons from April through November 1992. During this period, eight Landsat TM scenes, six ERS-1 SAR images, and four SPOT-HRV scenes were obtained. Each satellite overpass was accompanied by extensive ground- and aircraft-based measurements of surface and atmospheric conditions. The overall research goal was to investigate the seasonal hydrologic dynamics of the region and to define the information potential of combined optical-microwave remote sensing.

The Semi-Arid Land-Surface-Atmospheric Mountain Experiment (SALSA-MEX) is an interdisciplinary experiment proposed to investigate the strong influence of mountain topography on local and regional atmospheric stratification and subsequent impacts on surface water and energy balance (Goodrich et al., 1993). The proposed location is the semi-arid mountainous region of the San Pedro Basin, straddling the U.S.-Mexico border near southeastern Arizona. This experiment will combine measurements and modeling to increase our understanding of processes influenced by topography, such as enhanced precipitation, snowmelt, and recharge to groundwater aquifers.

FINDINGS: Preliminary research results from Monsoon'90 will be published in an upcoming special issue of *Water Resources Research*, (see appendix B), edited by W.P. Kustas (ARS, Beltsville) and D.C. Goodrich (ARS, Tucson). The 16 manuscripts to be published in that issue can be grouped under three general topics: (1) investigation of spatial and temporal variability of ground-truth data caused by environmental factors and measurements errors; (2) correction and interpretation of the remotely sensed data, including the potential for inferring geophysical and biophysical properties of the surface via remote sensing information; and (3) incorporating remote sensing data and other technologies in an attempt to model the hydrologic and surface energy fluxes over a range of spatial and temporal scales.

These results provide the theoretical foundation for the analysis of WG'92 data and planning of the SALSA-MEX experiment.

Analysis of data acquired during WG'92 has focused on two issues: (1) the synthesis of microwave and thermal spectral data to improve estimates of sensible heat flux density in the rangeland ecosystem (Moran et al., 1993), and (2) the use of optical spectral data for extraction of spatial and seasonal biophysical variables in sparsely-vegetated areas (Batchily et al., 1993). Work is currently underway to georegister the satellite data with digital elevation data and utilize a grid of meteorological stations to produce corresponding maps of air temperature, wind speed, humidity, and incoming solar radiation. With these regional data layers, it will be possible to use a Geographic Information System (GIS) to analyze hydrologic processes at the regional scale.

INTERPRETATION: Under the conditions observed at WGEW, modeling the mass and energy exchanges across the soil-plant-atmosphere interface and through the soil profile is particularly challenging. The preliminary results from the Monsoon'90 and WG'92 experiments, coupled with the extensive experimental data base, should aid the research community in addressing these challenges, provide a firm foundation for future large scale experimental efforts, and assist in the development and verification of improved methods for quantifying hydrologic and atmospheric fluxes for these environments.

FUTURE PLANS: Further research is already underway to address fully the Monsoon'90 and WG'92 objectives and to explore, analyze, and model the phenomena observed more fully. Additional efforts also will explore the transferability of the results to other semi-arid regions. In preparation for the proposed SALSA-MEX experiment, we plan to investigate and implement procedures for coupling an existing mesoscale model (Avissar and Peilke, 1989) with hydrologic and land surface characterization data layers derived from WG'92 satellite-based spectral images. This coupled model will allow investigation of the model sensitivity for application to topographically diverse regions and allow definition of such model input requirements as temporal/spatial resolution and accuracy. Once the model sensitivity and input requirements have been defined, the approach will be ready for application to high-elevation sites for calibration, validation, and subsequent investigation of regional hydrologic processes.

COOPERATORS: Bill Kustas, Karen Humes, ARS Hydrology Laboratory, Beltsville, MD; Dave Goodrich, Mark Weltz, ARS Southwest Watershed Research Center, Tucson, AZ; Alain Vidal, CEMAGREF-ENGREF Remote Sensing Laboratory, Montpellier, FRANCE; Other investigators from The University of Arizona, Utah State University, Los Alamos Laboratory, Jet Propulsion Laboratory, LERTS-France, IRE-Russia, USGS, and University of Maryland. Supplemental funding was provided by NASA (NASA IDP-88-086) and NASA-EOS (NAGW2425).

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BIDIRECTIONAL PROPERTIES AND MODELING OF REMOTE SENSING MEASUREMENTS OVER AGRICULTURAL LAND SURFACES

J. Qi, Physical Scientist; and M. S. Moran, Physical Scientist

PROBLEM: Quantitative analysis of remote sensing measurements for agricultural research studies is limited by the ability to separate surface-related signals from external factors such as sensor viewing geometries, atmosphere attenuations, and soil background variations. One of the most pronounced effects is the bidirectional properties of the land surfaces, which can produce more than 50% uncertainty when sensed at different viewing configuration. Consequently, to effectively utilize remote sensing measurements for the purpose of agricultural managements, it is imperative that the bidirectional effects be accounted for and quantified. The objective of this research is to quantify and model the bidirectional effects for agricultural land surfaces.

APPROACH: Multi-altitude remote sensing data were obtained from sensors on board satellite and high- and low-altitude aircraft at different sensor viewing angles at the Maricopa Agricultural Center, Maricopa, Arizona, on September 7 and 8, 1990. The sensors used in this study included the Advanced Solid-State Array Spectroradiometer (ASAS) (Iron and Irish, 1988) and an Exotech radiometer equipped with one Thematic Mapper (band 1) and three SPOT High Resolution Visible(HRV) filters. The 29 ASAS spectral bands range from 460nm to 860nm, while the Thematic Mapper and HRV bands cover blue (430nm-550nm), green (460nm-710nm), red (590nm-760nm) and near-infrared (740nm-950nm) regions. Three targets (pecan orchards, cotton canopy, and bare soil field), were selected to study the bidirectional properties of agricultural land surfaces. A total of eight bidirectional reflectance distribution function (BRDF) models were applied to the data sets. Based on these BRDF models, a sensitivity analysis of the remote sensing measurements to the sensor's view angle was made with respect to both spectral reflectances and vegetation indices.

FINDINGS: The bidirectional effects were not only dependent on the sensors' viewing configuration, but also on the surface types (Figures 1 and 2). In general, the backscattering direction (negative view angles) resulted in higher reflectances than the forward scattering direction (positive view angles). The "bot spot" effects (a phenomenon that reflectances are much higher when the sensor is looking at the target in the same direction as the illumination source [Sun] than in other directions) were more evident for the ASAS data (Figure 1) than those for the aircraft data (Figure 2). This is due mainly to the difference in the sensor's instantaneous field of view (IFOV) or so called "scaling" effects.

The bidirectional properties of the three selected targets can be modeled with BRDF models. Data in Figure 3 show the comparison between the measured and simulated bidirectional reflectances of the pecan trees with a BRDF model by Verstraete and Pinty (1990), indicating that BRDF models can be used to correct for bidirectional effects. Vegetation indices derived from the bidirectional reflectances did not normalize the oblique viewing effects (Figure 4). The normalized difference vegetation index (NDVI) increased when the sensor viewing direction changed from backscattering to the forward scattering direction, while the soil adjusted vegetation index (SAVI) decreased for the pecan canopy. However, for the cotton canopy, the SAVI decreased with view angles changing from backscattering to forward direction, while the NDVI varied little. The NDVI differences between the nadir and off-nadir view angles were 1%, 19% and 26% for the cotton, pecan, and soil targets respectively, while those of the SAVI were 22%, 21% and 23% for the three selected surfaces.

INTERPRETATION: The bidirectional reflectance measurements are strongly dependent on the sensors' viewing configuration. Most pronounced effects were found in the backscattering direction. BRDF models can be used to correct these effects. Vegetation indices derived from bidirectional measurements were also dependent on sensor viewing geometries. This suggests that the bidirectional effects could not be normalized by vegetation indices. Therefore, to characterize quantitatively agricultural surface properties with remote sensing measurements, it is necessary to quantify the bidirectional effects with BRDF models.

FUTURE PLANS: A more thorough analysis of the data sets will be continued for the next year to characterize the bidirectional properties of different types of crops. Sensitivity studies will be conducted to quantify the uncertainties due solely to the bidirectional effects of both reflectances and vegetation indices. A total of eight BRDF models will be tested to select the most suitable model(s) for agricultural land surfaces. Based on the sensitivity analysis, a set of sensor configurations that would result in minimal uncertainties will recommended, and finally a practically operational algorithm will be developed to correct the bidirectional effects to provide farmers with consistent quality remote sensing data products.

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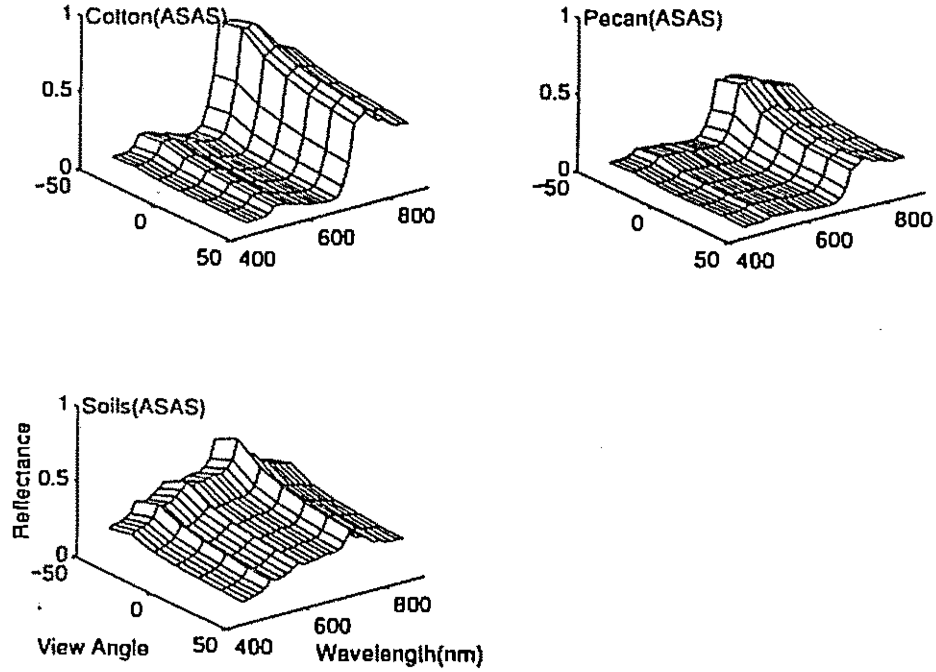

Figure 1. Spectral reflectances of the cotton (a), pecan(b), and soil(c) canopies measured with a ASAS sensor at an altitude of 5300 meters above ground at different view angles(negative:backscattering, positive:forward scattering). Hot spot effect noticeable at view angle of -30^0 ; the solar zenith angle at the time of measurements was 28^0.

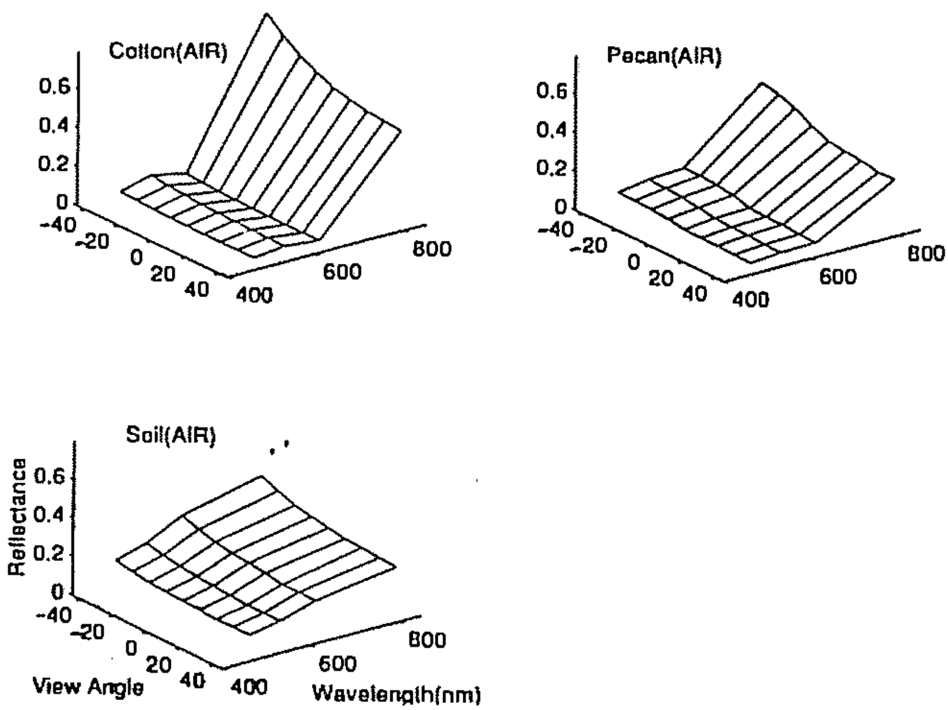

Figure 2. Spectral reflectances of the cotton (a), pecan(b), and soil(c) canopies measured from an aircraft at an altitude of 150 meters above ground at different view angles(negative:backscattering, positive:forward scattering).

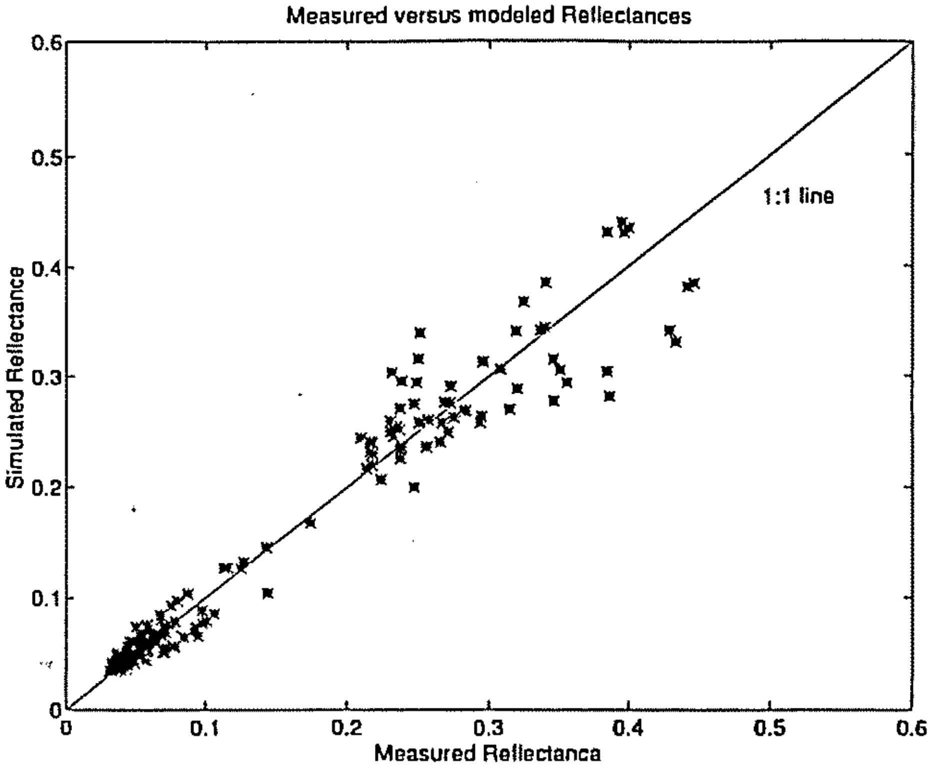

Figure 3. Comparison between measured and modeled spectral reflectances in the ASAS spectral region.

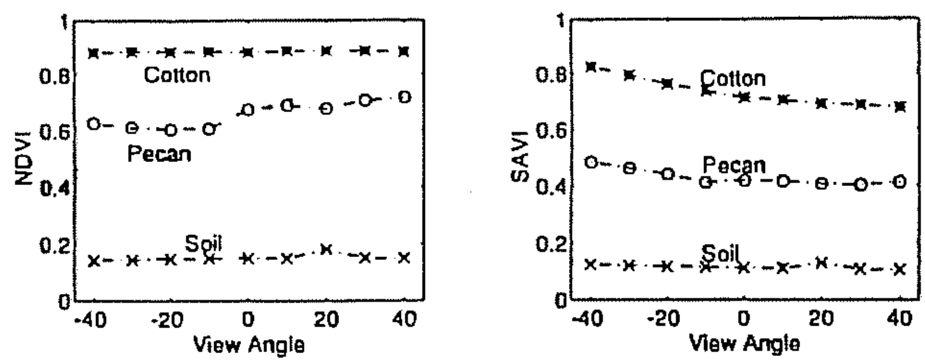

Figure 4. Bidirectional effects on NDVI (a) and SAVI(b) with aircraft measurements.

SPECTRAL BAND SELECTION FOR A MISSION-SPECIFIC FARM MANAGEMENT REMOTE SENSING PLATFORM

T. R. Clarke, Physical Scientist

PROBLEM: The body of knowledge on remote sensing applications for farm management has increased steadily over the past two decades, and several relationships between crop health and the electromagnetic radiation the plant reflects or emits have been documented. For example, the reflected red and near infrared radiation from the earth's surface can be compared to quantify the amount of vegetation present (a vegetation index), while the thermal radiation emitted from a plant's leaves is directly related to the amount of water stress the plant is experiencing.

These and other phenomena have been recorded in the literature but the technology for practical implementation did not exist at the time.

Sensor technology has blossomed in recent years, with highly sensitive imaging detectors becoming more affordable. Simultaneously, the computer industry has made advances which allow the rapid processing of large numbers of images. Recently developed Geographic Information Systems (GIS) and the satellite Global Positioning System (GPS) can be combined to allow the rapid transfer of images to surface maps for near real-time delivery of a product to a user. In short, the means are now available to develop remote sensing platforms specifically designed to assist the farm manager both in increasing farm productivity and conserving natural resources.

A goal was set to determine what spectral bandwidths would provide the most useful information to farm managers using today's technology and state of knowledge. As the cost of such a service to farm managers would be directly related to the number of sensors, the total number of bands selected would be kept reasonably low and prioritized by economic significance.

APPROACH: A search of the scientific literature was initiated to determine what portions of the electromagnetic spectrum were most useful in detecting stress from a variety of causes in agricultural systems. In cases of conflicting results or insufficient detail, the hypotheses were tested using historical field data collected by the U.S. Water Conservation Laboratory or published data from other sources. The search was limited to the visible and infrared regions of the spectrum and were further confined to the spectral "windows" where the atmosphere is relatively transparent. An additional criterion was that the detector hardware and processing algorithms must either be immediately available or capable of being developed to an operational stage within the next two years.

FINDINGS: The usefulness of stress detection bands is greatly enhanced when compared to a vegetation index, as the relevant response is proportional to the amount of vegetation present. The red and near-infrared bands used to compute vegetation indices were therefore given the highest priority. Vegetation indices can be used directly as stress indicators by comparing images taken on a frequent basis.

The thermal band is a good indicator of any stress which affects stomatal resistance and will hopefully become more useful under partial canopy conditions with the development of the VIT trapezoid as described by Moran and Clarke in this volume.

The green band shows promise as a detector of nitrogen deficiency and may be useful in estimating Leaf Area Index when the target is viewed from several look angles.

A Fraunhofer line detector (FLD) measures the fluorescence of inefficiently photosynthesizing plants in the Hα absorption line of solar radiation. The potential of this detector of general crop stress has not been fully investigated because the extremely narrow bandwidth and low light level made instrumentation difficult. New developments in narrow band filtration and CCD detectors may allow the production of a small FLD.

No direct use for mid-infrared (1.2 - 2.5 μm) sensors has yet been found for farm management purposes. The response of these wavelengths to crop water stress is minimal.

Preliminary list of recommended bands for crop stress detection:

Priority	Color	Center	Bandwidth	Function
1.	Near infrared	0.790 μm	.04 μm	Growth rate, yield prediction, vegetative material
2.	Red	0.665 μm	.02 - .03 μm	Growth rate, yield prediction, chlorophyll
3.	Thermal	10.7 μm	0.8 μm	Crop water stress, general stress, soil surface moisture
4.	Green	0.550 μm	.02 - .04 μm	Nitrogen deficiency, bidirectionally-derived LAI
5.	Fraunhofer line	0.6563 μm	0.0001 μm	Photosynthetic efficiency

INTERPRETATION: Many of the remote sensing systems in use today use wide-band sensors as the detectors had relatively low sensitivity at the time they were developed. Current technology has provided much improved sensitivity, allowing narrower bandwidths and hence greater signature differentiation. Many techniques developed over ten years ago were not implemented because the sensor technology did not exist to make them economically feasible at the time. Examples of this are a Green/Red algorithm for detecting nitrogen deficiency, which would be optimized by using narrower bandwidths than are found on LANDSAT and SPOT satellites and the portable radiometers designed to mimic them, and the Fraunhofer line detection of canopy fluorescence, which requires an extremely narrow bandpass filter and very sensitive detector. Improvements in vegetation indices can be expected by narrowing the bandpasses of the red and near-infrared sensors, particularly by avoiding atmospheric absorption features in the near-infrared.

FUTURE PLANS: The review of the literature will continue through early 1994. Radiometers will be modified or manufactured to test the resulting band recommendations during an intensive field campaign in the summer of 1994.

COOPERATORS: This project was undertaken as part of a Cooperative Research and Development Agreement with a private company which wishes to remain anonymous.

USING STAND VARIABILITY TO ESTIMATE LEAF TEMPERATURE IN PARTIAL CANOPIES

T.R. Clarke, Physical Scientist; and M.S. Moran, Physical Scientist

PROBLEM: As the soil moisture in the root zone of a plant diminishes, the water available for evaporation through the leaf stomates also decreases. Less solar energy is used to evaporate water, and, as a result, the leaf temperature increases relative to air temperature. Infrared thermometers can detect this temperature change, and the method has found use in detecting water stress in crops. However, the presence of a hot soil background in the infrared thermometer's field of view causes large errors in the measured canopy temperature. This limits the usefulness of an airborne or orbital detector to crops with full vegetative cover, which often occurs only late in the season. A means of estimating crop canopy temperature in the presence of soil background is needed.

APPROACH: A vegetation index (VI) mathematically compares the reflectance of red and near infrared light from the Earth's surface to produce a value directly related to the amount of vegetation present. Using a VI as one axis and the surface temperature minus air temperature as the other axis, a two-dimensional space can be theoretically defined which delineates all possible temperature/VI pairs that can be found over a particular crop. This space is shaped somewhat like an airplane's tail fin (Fig. 1) and has been dubbed the VIT Trapezoid. The derivation of the trapezoid is discussed by Moran and Clarke elsewhere in this volume.

A low cost, lightweight digital camera system was assembled to collect images in red and near infrared light simultaneously. The system was flown with a thermal infrared scanner over wheat, melons, and cotton in May, July, and October 1993. Ground measurements of canopy temperature and bare soil reflectance were made during the July and October flights.

FINDINGS: All fields overflown showed substantial variability in stand when imaged at a two-meter spatial resolution. Scattergrams of Temperature/VI pairs derived from uncalibrated digital numbers showed clear, linear trends of points. Linear regressions through these groups of points appeared to intersect the top and bottom lines of the VIT trapezoid near the actual temperatures of the canopy and soil, respectively.

The digital cameras were found to have a nonlinear response to radiance, which must be better defined and corrected in image processing before accurate vegetation indices can be calculated. Also, an atmospheric effect was seen in the thermal scanner results, and this must be corrected before accurate surface temperatures can be determined.

INTERPRETATION: The cannpy temperature cannot be determined accurately from a single pixel or from a group of pixels with a uniform but incomplete cover. The soil background, depending on the moisture content of its surface, may have a widely varying temperature, which, in turn, leads to a range of possible canopy temperatures as illustrated in Figure 2. However, a variable stand in a field with uniform soil surface moisture will produce a linear group of points as shown in Figure 3, which hypothetically acts as a pointer to the actual canopy temperature.

FUTURE PLANS: Customized image processing techniques are required to correct the multispectral images for reflectance and temperature. These will be developed in the near future. If the results of this year's experiments prove successful, a better digital imaging system will be sought, and image processing will be more automated in an attempt to deliver useful farm management information in a timely manner.

COOPERATORS: The May and October flights were made in cooperation with Henry Brubaker of Martori Farms in Aguila, Arizona. The July flights were made over The University of Arizona Maricopa Agricultural Center with assistance from Karim Batchily and Faizur Rahman of the Department of Soil and Water Science of The University of Arizona and David Ammon of Aerial Images, Tucson, Arizona. An aircraft from the Institute for Technology Development, Space Remote Sensing Center of NSTL Station, Mississippi, also participated in the July experiment. Participants in the October experiment included Dr. Giovanni Narciso of AQUATER S.p.a. of S Lorenzo in Campo, Pesaro, Italy; and François Cabot of the Laboratoire d'Etudes et de Recherches en Teledetection Spatiale (LERTS) Toulouse, France.

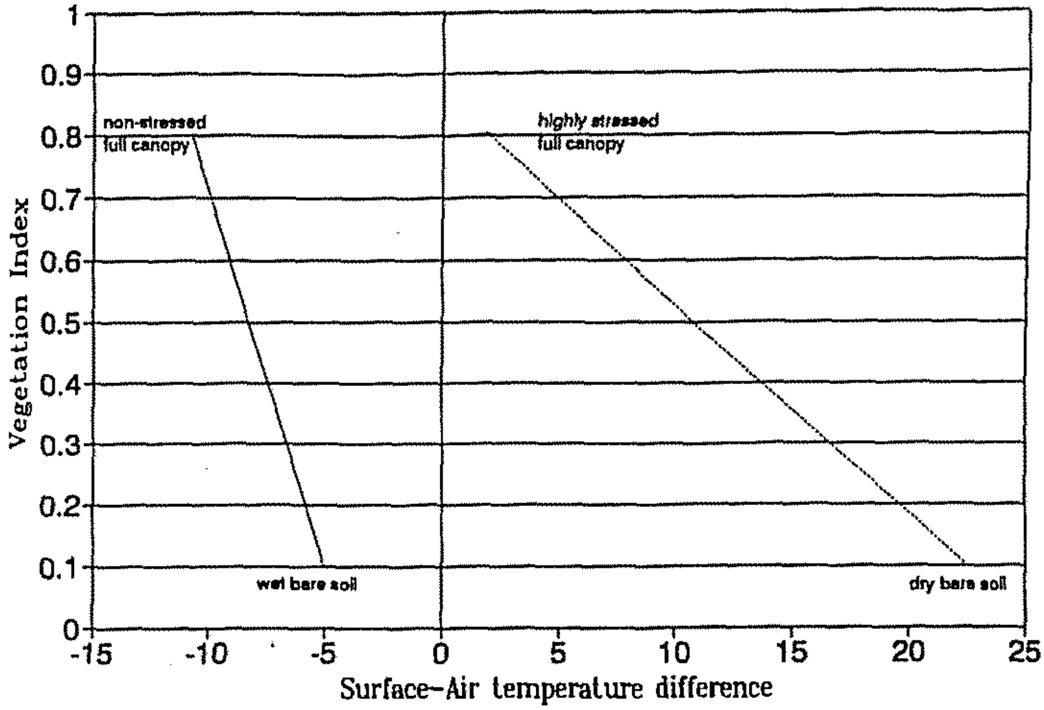

Figure 1. The VIT trapezoid, outlining all the possible locations of Vegetation Index/surface- minus air-temperature pairs. The dimensions of the trapezoid are unique to the crop type and meteorological conditions.

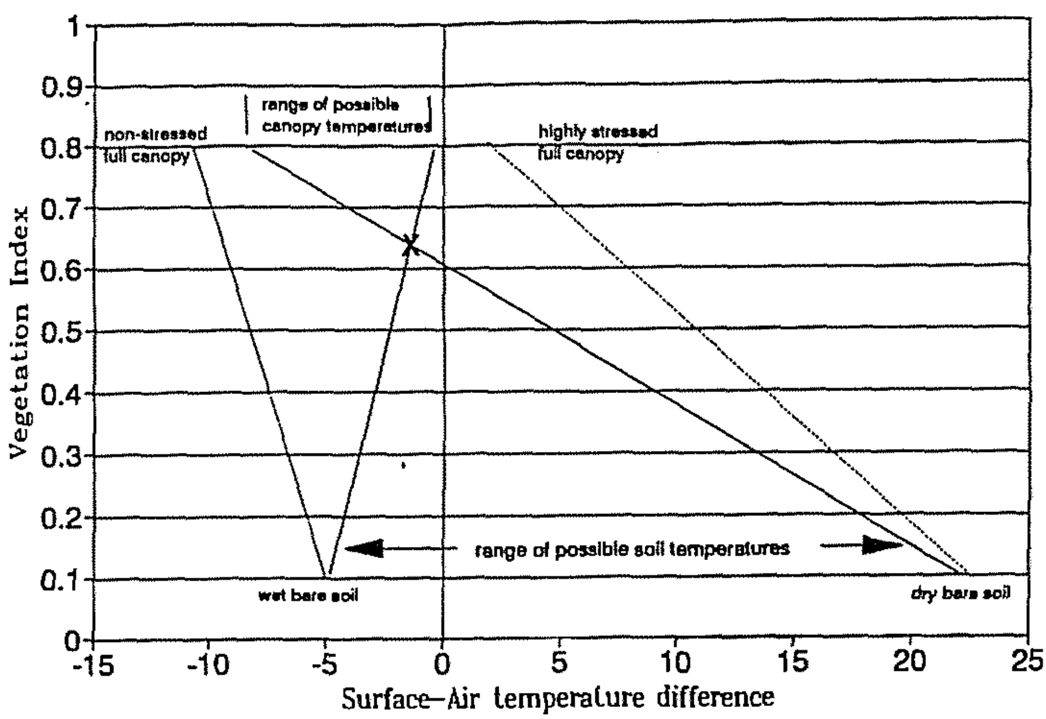

Figure 2. Range of possible actual canopy temperatures when only a single VIT pair (X) is known.

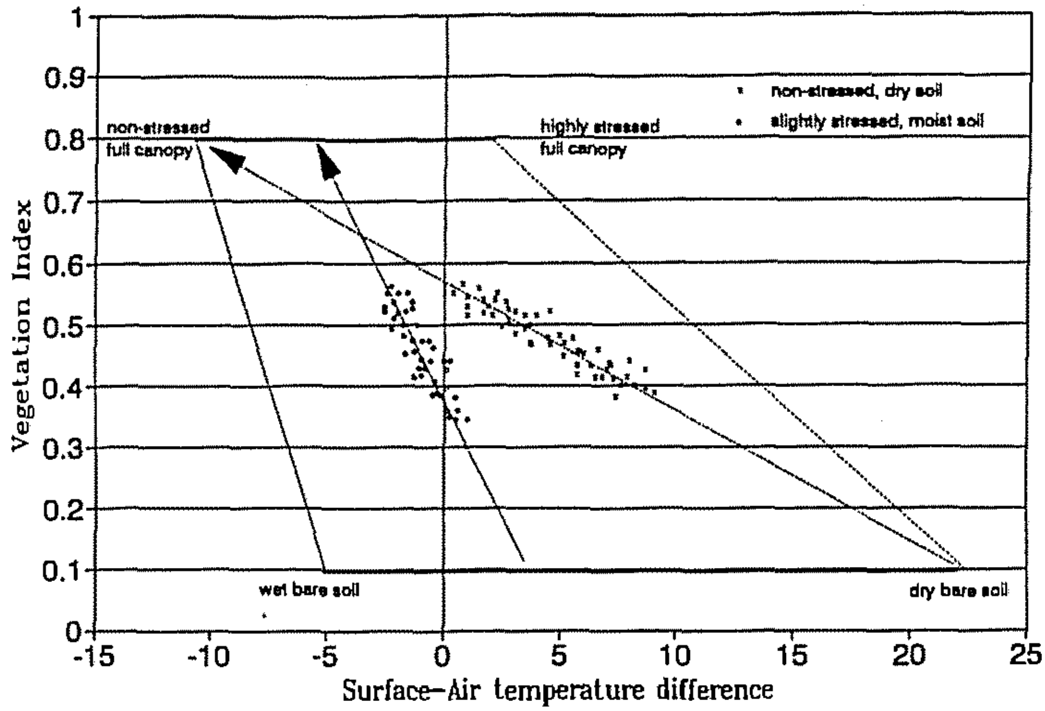

Figure 3. Hypothetical VIT pairs in fields with variable stands in two scenarios: a nonstressed crop with a completely dry soil surface (x), and a crop experiencing mild water stress with a damp soil surface (o). Note that, paradoxically, the *nonstressed crop* can have warmer mixed-pixel temperatures than the stressed crop in this special case.

GUAYULE LATEX EXTRACTION AS RELATED TO SHRUB STORAGE AND TREATMENT

F.S. Nakayama, Research Chemist; and D.A. Dierig, Research Geneticist

PROBLEM: The rubber from the guayule plant recently has been shown to be nonallergenic compared to the Hevea latex rubber products, which can cause various types of allergic responses ranging from mild dermatitis to anaphylactic shock. This new information greatly improves the chances for the successful commercialization of the guayule plant as a source of natural rubber latex for the fabrication of medical and consumer products. The basic ingredient for producing such latex products is a stabile suspension of individual rubber particles. Obtaining latex from guayule, however, is more complicated than from Hevea. The rubber particles in guayule are formed and reside in the plant cell, whereas those for Hevea occur naturally as a suspension in the sap material. Thus, guayule rubber particles must be removed from the shrub by an additional extraction process. Furthermore, the integrity of the individual rubber particle must be maintained throughout the production of the latex including (a) the rubber in the shrub, (b) the extraction process, and (c) the latex suspension derived from step (b). Existing laboratory and industrial organic solvent extraction procedures are unsuitable for guayule latex preparation since the rubber particles become agglomerated to form a solid rubber matrix during the process. The objectives of this study are to develop rubber extraction methods and shrub handling techniques to maximize the quality and quantity of guayule latex rubber yields.

APPROACH: For the initial phase, the extraction procedure and the effects of various type of plant treatment will be examined before any full-scale process can be developed for producing large quantities of guayule latex suspension for fabricating rubber products,

Latex Extraction: Water-based latex extraction procedures were used similar to those described by Cornish and Backhaus (1990) for isolating rubber transferase enzymes. The formulation, however, was simplified (no mercaptoethanol and phenylmethylsulphonyl) since we were interested only in getting the rubber particles in latex form and not maintaining the active enzyme fraction. The extracting solution consisted of 100 mM Tris-buffer (pH 7.5), 1% ascorbic acid, 50 mM KF, and 5 mM $MgSO_4$. Polyvinypyrrolidone was added to the mix during the grinding process. The actual extraction procedure consisted of homogenizing the bark with the extracting solution in a Waring-type blender, filtering through cheesecloth, centrifuging the filtrate, and finally collecting the latex by skimming off the resultant creamy rubber particles that floated on the extracting solution surface.

Shrub Handling & Treatment: Twelve-year-old (variety 593 and 11591) and seven-year-old (variety N565-II) guayule plants were used in the study. Branches were cut from several plants and consolidated. The stems consisting of 5 mm and larger diameter were cut into 25.4 mm sections. The bark was separated from the wood by pounding the stem section and peeling off the bark from the wood. The bark was further cut into 6 mm sections for homogenizing. For the drying experiment, the bark was dried for various periods in the laboratory. Other portions of the bark also were stored in the freezer at -10 C or the refrigerator at 1 C. In addition, the bark was frozen with liquid nitrogen (-195 C).

FINDINGS: Approximately 2.5% latex rubber was extracted from the bark by the physical grinding and chemical water-based extracting solution used. Total rubber content, based on organic solvent extraction, for similar samples ranged from 12 to 16%. Thus, there is room for improvement in increasing the amount of rubber latex extracted. However, with the organic solvent extraction method, the resin component is removed, which would interfere with the fabrication of latex-based products.

Recovery of the latex was unchanged when the samples were stored under refrigeration for 17 days (Table 1). Less rubber was obtained when the sample was frozen than when refrigerated (Table 2). Furthermore, freeze-thawing the bark caused a drastic reduction in latex recovery. Freezing the bark at liquid nitrogen temperature or parboiling for 10 minutes at 100 C caused latex recovery to be practically zero. Liquid nitrogen freezing is used in the total rubber content procedure to help in the grinding of the plant sample. Parboiling is used in the water-flotation method of extracting rubber from the whole plant.

The drying of the sample also reduced latex recovery (Table 3). At approximately 50% and less water content, a large decrease in rubber removal occurred. Thus, care must be taken with shrub handling between harvest and processing to avoid excessive drying of the shrub.

INTERPRETATION: Rubber latex yield using a simple water-based laboratory extraction process was only 2.5%, but this could be greatly increased by using plant grinders or ball mills, press-type filter extractors, and continuous centrifuge equipment. Plant drying caused a decrease in the amount of extractable latex; thus, the shrub must be maintained as fresh as possible before latex extraction. This also implies that the shrub should be processed on-site or as close to the field to avoid plant desiccation and latex degradation. Possibly, the grower could process the shrub and the latex could be collected and stored in refrigerated tanks with the proper chemical or enzyme stabilizers and anti-oxidants for later transport to the rubber fabrication station. Because a freeze-thaw cycle imposed on the shrub can decrease latex extractability, care must be taken to avoid shrub processing during mid-winter.

FUTURE PLANS: Studies on the extraction of guayule latex, latex stability, and application of stabilizers and anti-oxidants will continue and be expanded. Information on field handling of shrubs, especially as it relates to the drying and extractability of the latex, will be acquired. The interrelations between latex yield and guayule variety will be developed for germplasm improvement. Methods for increasing the quantity of latex produced will be developed. Sufficient quantities of latex will be produced for determining storage stability, for characterizing its chemical and physical properties, and for making latex rubber products. Economic analysis based on the extracting and processing of latex will be developed.

COOPERATORS: K. Cornish, USDA-ARS-PWA, Albany, CA; W.W. Schloman, Jr., Department of Polymer Science, University of Akron, Akron, OH.

REFERENCES: Cornish, K. and Backhaus, R.A. Rubber transferase activity in rubber particles of guayule. Phytochem. 29:3809-3813. 1990.

Table 1. Effect of storage length on latex recovery. (Variety 11591)

Time (day)	Latex (%)
0	2.61 a*
10	2.57 a
17	2.37 a

*Means followed by the same letter are not significantly different at the 0.05% probability level.

Table 2. Effect of sample treatment on latex recovery. (Variety N565-II).

Plant Treatment	Latex (%)		
	I	II	III
Fresh	----	2.49 a*	2.34 a
Refrigerate	2.11 a	----	
Freeze	----	2.11 b	2.16 a
Freeze/thaw/refrig.	0.21 b		
Freeze/thaw/freeze	----	0.11 c	0.00 b
Freeze (liquid N_2)	0.00 c	----	----
Parboil/freeze/thaw/freeze	----	----	0.06 b

*Column means followed by the same letter are not significantly different at the 0.05 probability level.

Table 3. Effect of drying of guayule bark on latex extraction.

	Water Content (%)	Latex (%)
593	102.4 (fresh)	1.99
	70.0	1.95
	53.6	1.77
	11.7	0.79
	6.0 (air dry)	0.23
11591	89.2 (fresh)	2.42
	55.5	2.26
	43.1	2.06
	31.5	2.15
	25.5	1.39

METHANOL EFFECTS ON COTTON YIELD

F.S. Nakayama, Research Chemist

PROBLEM: Researchers are continually looking for methods to improve crop production. Recently, Nonomura and Benson (1992) reported on a methanol treatment for increasing plant growth and yield and conserving water for a variety of crops, including cotton. Because of the profound scientific impact of this article and the world-wide publicity associated with it, independent studies were needed to validate the claims about methanol treatment. Thus, investigations were initiated to confirm the work on methanol effects for cotton and possibly expand it to other arid-adapted new crops.

APPROACH: Cotton plants (Deltapine 5415 and Pima S-7) were treated with various combinations of methanol solutions whose composition and plant application closely followed the protocol set up by the various researchers involved with cotton and the chemical agent. The experiment was conducted at the University of Arizona Maricopa Agricultural Center, Maricopa, Arizona. The experimental design was a randomized complete block with six replications. Each treatment block consisted of four rows of cotton spaced 1 m apart and 13.7 m long. The treatment included a (A) "Check" with no spray treatment; (B) "Methanol" with 30% methanol and wetting agent (0.05% Triton X-100); (C) "Nutrient" with 1% urea, 0.01% iron chelate, and wetting agent; and (D) "Methanol+Nutrient", the complete solution including parts (B) and (C). Six separate methanol applications were made that began on June 16 and ended on August 6, 1992. Application rate was 187 L/ha (20 gal/Ac). A tractor-mounted spray rig, calibrated before each run, was used to apply the solution just above the plant canopy. Cotton cultural management essentially followed practices used at the Center. However, irrigation applications for the last two scheduled periods were delayed to impose additional water stress on the plants.

FINDINGS: No effect of methanol application at the 30% concentration level was found on plant height, boll weight, or cotton yield for the Pima S-7 and DP 5415 varieties (Tables 1 and 2, respectively). Information on lint quality is not available at present. Similarly, no effect of the methanol treatment on photosynthesis or photorespiration was observed for the two set of measurements taken (Table 3).

The whitefly nymph population was significantly lower in the "Methanol+nutrient" treatment compared to the "Check" on August 10, approximately seven weeks after the methanol treatment began, and the difference continued through August 20 (Table 4). The effect of methanol was not evident on September 2, approximately four weeks after the spray treatment ended on 6 August. There was no effect of methanol on the egg population, however. It is not known whether direct contact of the methanol with the nymph or an indirect effect of the chemical on the leaf surface property had affected the whitefly nymph population.

INTERPRETATION: No evidence or even a hint of methanol increasing cotton production was obtained with the rate and application system used in this study. It does not appear fruitful to examine further aspects of methanol treatment such as application rate, time and number of applications, plant stress, or the combinations at this time.

FUTURE PLANS: The study will not be continued unless other strong evidences are presented that show significant effects of methanol on cotton plant growth, yield, and water savings.

COOPERATORS: J.M. Nelson, The University of Arizona, Maricopa, AZ; H. Flint, USDA-ARS-WCRL, Phoenix, AZ; R.L. Garcia, USDA-ARS-USWCL, Phoenix, AZ.

REFERENCES: Nonomura, A.M. and Benson, A.A. The path of carbon in photosynthesis: Improved crop yields with methanol. Proc. Natl. Acad. Sci. 89:9794-9798. 1992.

Table 1. Effect of methanol treatment on plant height, boll weight, and seed cotton yield of Pima S-7.

Treatment	Plant height (m)	Boll weight (g/boll)	Seed cotton yield (kg/ha)
Check	1.24 a*	3.41 a	3674 a
Methanol	1.23 a	3.33 a	3737 a
Nutrients	1.22 a	3.39 a	3749 a
Methanol + nutrients	1.22 a	3.34 a	3669 a

*Means followed by the same letter are not significantly different at the 0.05 probability level.

Table 2. Effect of methanol treatment on plant height, boll weight, and seed cotton yield of DP 5415.

Treatment	Plant height (m)	Boll weight (g/boll)	Seed Cotton yield (kg/ha)
Check	1.30 a*	5.21 a	5449 a
Methanol	1.27 a	5.18 a	5367 a
Nutrients	1.30 a	5.05 a	5264 a
Methanol + nutrients	1.31 a	5.12 a	5472 a

*Means followed by the same letter are not significantly different at the 0.05 probability level.

Table 3. Effect of methanol treatment on photosynthesis and photorespiration of DP 5415 cotton.*

Treatment	17 June Photosynthesis (μmol m^{-2} s^{-1})	17 June Photorespiration (μmol m^{-2} s^{-1})	14 July Photosynthesis (μmol m^{-2} s^{-1})
Check	20.9 ± 4.9	15.8 ± 3.9	27.2 ± 4.6
Methanol + nutrient	22.8 ± 3.7	16.7 ± 2.4	25.5 ± 5.4

*Three repeated measurements were made on six leaves in each treatment.

Table 4. Effect of methanol treatment on egg (E) and nymph (N) population of sweetpotato whitefly, *Bemisia tabaci* (Genn.), on DP 5415 cotton.[1]

Date	7/15		7/30		8/10		8/20		9/02	
Treatment	E	N	E	N	E	N	E	N	E	N
Check	7.2	2.4	2.8	6.1	3.1	2.5 a	16.2	10.5 a	11.2	4.3
Methanol	7.6	3.2	3.7	4.4	4.9	1.7 ab	14.5	4.8 b	17.7	5.1
Nutrient	9.0	3.6	3.4	5.2	3.7	1.2 ab	13.2	6.5 ab	15.3	4.5
Methanol + nutrient	7.4	3.1	4.0	6.8	2.9	1.1 b	14.8	4.3 b	19.0	4.2

[1] Ten leaves/plot collected from the 5th main stem node from the top of the plant. One 3.88 cm^2 disk/leaf from quadrant 2 examined for eggs and nymphs. Means followed by the same letter are not significantly different at the 0.05 probability level.

EFFECTS OF METHANOL ON PLANT GROWTH

S.B. Idso, Research Physicist; R.L. Garcia, Plant Physiologist; and
B.A. Kimball, Supervisory Soil Scientist

PROBLEM: In a series of press releases and a paper published in the *Proceedings of the National Academy of Sciences*, two scientists have said that the spray application of aqueous methanol to plant leaves can stimulate subsequent plant growth by 50 to 100% by dramatically decreasing photorespiration. This claim has created a mild sensation world wide and has resulted in numerous requests for information from farmers and the general public. Hence, an effort was begun this year to see if controlled studies would verify or dispute the claimed benefits of methanol for basic plant physiological processes.

APPROACH: On three different weeks in September 1993, sections of field-grown cotton were sprayed with a 30% methanol solution with surfactant 3, 2 and 1 day, as well as 2 hours, before measurements of net photosynthesis, gross photosynthesis, and -- by difference -- photorespiration were made on upper sunlit leaves of the plants with an LI-6200 portable photosynthesis system. Both well-watered and highly-stressed plants were tested. Net photosynthesis measurements were also made of sour orange tree leaves that had been grown for 5.5 years at either 400 or 700 ppm CO_2. Measurements of control and methanol-targeted leaves were made on 12 cloudless days between 13 May and 24 June 1993, after which the methanol-targeted leaves were sprayed with a 40% solution with surfactant on 27 June and 3 July. Photosynthesis measurements were then made again on 30 June and 1, 2, 6, 8, and 9 July.

FINDINGS: None of the measurements made on the cotton leaves on any individual day revealed any significant differences between the control and methanol-treated plants. Rates of net photosynthesis, in particular, were identical in both treatments, in spite of the fact that photorespiration consumed over a third of the gross photosynthate produced.

In the sour orange tree study there was a strong carbon dioxide effect. The 75% increase in CO_2 enhanced net photosynthesis by 75% at a leaf temperature of 31°C, doubled it at 35°C, and tripled it at 42°C, raising the upper-limiting leaf temperature for positive net photosynthesis by approximately 7°C. Once again, however, there was no indication of any effect of the methanol applications.

INTERPRETATION: Our findings suggest that in the plants we studied -- which have been reported to be responsive to methanol -- there is no increase in net photosynthesis due to a reduction in photorespiration caused by methanol treatment.

FUTURE PLANS: As our results are contrary to those claimed by the originators of the methanol hypothesis, we will probably conduct further explatory studies of this concept in the coming year.

COOPERATORS: K.E. Idso and J.K. Hoober (Botany Department, Arizona State University); J.R. Mauney (Western Cotton Research Laboratory, retired).

BREEDING IMPROVEMENTS OF GUAYULE GERMPLASM

D. A. Dierig, Research Geneticist; A. E. Thompson, Research Geneticist; and
F. S. Nakayama, Research Chemist

PROBLEM: Development and commercialization of guayule as a potential rubber crop depends on higher yielding germplasm. In addition to yielding rubber, guayule produces significant amounts of resins and other potentially useful by-products that also will have a significant impact on its commercialization. Recently, hypoallergenic medical products have been successfully developed with latex from guayule, without the allergic reactions from latex-sensitive persons In developing guayule as a viable rubber crop, we have found extensive variation for characteristics that are related to rubber and resin yield, implying that simple selection would be possible. Apomixis (asexual reproduction by seed) then allows the plant to carry the trait to the subsequent generations. However, new generations do not always possess the desired characteristics. This is due in part to periodic sexual reproduction and also environmental influences on genetic traits. The objective of our breeding program is to generate germplasm containing variability for traits that correlate to yield, and, once promising germplasm is identified, to develop breeding strategies that enable us to control that variation. The ultimate goal is to develop new germplasm and varieties with sufficient rubber and resin yields for full commercialization of guayule.

APPROACH: A study to determine the degree of resemblance of offspring to parent plants and estimate the amount of genetic variance was completed this year. Twenty-four families of 14 offspring each in two replicates, were harvested and compared to measurements of the parents harvested at the same age. In addition to the measurements of traits related to yield; which included rubber and resin content, plant dry weight, and rubber and resin yield; isozyme patterns also were examined. Isozymes have an advantage over other traits because, in addition to having Mendelian inheritance, they are not influenced by the environment, and can provide a direct estimate of how much genetic variation occurs between parents and offspring. A value for heritability was calculated for yield traits by the regression of the parent plants to the mean of each 14 progeny families. The practical application of this study is to determine the best breeding method for yield improvement.

A third-year progeny test from 31 apomictic lines compared to two standard USDA lines was harvested this year. Yield data were collected on 12 plants from each line over four replications and compared to the standard lines. Plants were analyzed individually for rubber and resin content. Data collected from the previous 1992 season (2-year-old plants) also were compared to this year's data. Seeds were collected from promising selections.

Two-year-old plants from 10 sexual reproducing lines (diploids) were harvested this year. Thirty plants from each line were analyzed individually for rubber and resin content. This study is part of a recurrent selection breeding strategy aimed at increasing rubber content by taking advantage of new recombinations produced by diploids and selecting the highest rubber percentages for the next generation. This process is then repeated for each generation.

Other studies included the third-year harvest of plants in the Guayule Uniform Regional Variety Trial comparing 13 new lines to two standard USDA lines. Eight of these lines are from this program in cooperation with Dr. D.T. Ray. Analyses have not been completed from this study. A plant density study was conducted to determine if it is feasible to harvest plants at 2 years when planted at closer spacings with higher yielding selections instead of 3 years is in progress. These analyses have not yet been completed.

FINDINGS: The heritability estimates calculated for yield traits between parents and progeny were very low. Fresh or dry weight, rubber and resin content, and rubber and resin yield were not significantly different from zero in these regressions. A consistent amount of variation was found in isozyme patterns of progeny compared to parents.

Nine of the 31 lines harvested this year had rubber yields greater than 150% of the two standard USDA lines average. The best rubber yield for 1993 in this study was G7-15, which yielded over 200% of this average. Five of the nine also were 150% better than the standard lines in the second year (1992). One of the nine lines, G7-11, bad the highest yield of all last year (1992), which was double the yield of almost any other line in that study. This year the rubber yield from line G7-11 was about the same as the 1992 season. The best of these lines will be included in the next Guayule Uniform Regional Variety Trial across 4 southwestern states, to be planted spring of 1995.

A wide range of variability was found among the 2-year-old diploid population for all measured traits. Rubber contents ranged from 3.7% to 10.0%. Rubber yields ranged from 643 kg/ha to 1870 kg/ha. Twenty percent of the plants analyzed had rubber contents greater than 7%, and 6% of the plants bad rubber contents greater than 8%.

INTERPRETATION: The low heritability estimates suggest that parent plants are not good indicators of progeny performance. There is a large environmental effect on yield traits. This implies that a family selection breeding strategy would be more advantageous than single plant selection. The isozyme results indicate that the rate of apomixis varies significantly between lines.

Concentrated breeding effort will focus on the nine best yielding lines, using a family selection method. It would be more feasible to harvest line G7-11 at the second year rather than wait until the third. This could greatly increase the grower profits and provide the opportunity to plant at a closer field spacing since they will be mature in two years, and, thereby, increase rubber yield on a per acre basis. Based on rubber yield per acre per year, this line has good potential for adaption to a two-year cropping system.

The extreme amount of variation observed was expected in the open pollinated diploid population. There was a normal distribution of rubber contents from the plants analyzed. Progeny of plants from the high end of the curve will comprise the next generation and will be recurrently selected. Each generation progressively should move the mean of this curve upwards.

FUTURE PLANS: We will continue our effort developing the single plant selections and the recurrent selection of sexual diploids. We hope to expand isozyme identification for use as genetic markers to obtain more precise estimates to characterize lines for outcrossing and heritabilities. We also plan to incorporate Polymerase Chain Reaction (PCR) technology to our program. This technique amplifies small quantities of DNA from a plant and shows if variation is present between plants. The variation detected would be a total result of genetic contribution since environmental influence is not a factor. New germplasm will be collected and evaluated from Fort Stockton, Texas. Close coöperation will be taking place at this site because of the large amount of germplasm already established there.

COOPERATORS: D. Ray, The University of Arizona, Plant Science Department, Tucson, AZ; M. Foster, Texas A&M Experiment Station, Ft. Stockton, TX.

GERMPLASM IMPROVEMENT AND COMMERCIALIZATION OF LESQUERELLA

A.E. Thompson, Research Geneticist; D.A. Dierig, Research Geneticist;
F.S. Nakayama, Research Chemist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: Development of lesquerella as a new industrial oilseed crop will contribute significantly to the improvement of U.S. agriculture and the general economy of the country. The United States depends completely upon imported castor oil, a strategic material, for its total supply of hydroxy fatty acids. The unique chemical structure of lesquerolic acid in lesquerella seed oil, which is slightly different from that of ricinoleic acid in castor oil, offers distinct advantages for development of new industrial applications as well as a partial replacement for castor oil. Initial genetic and agronomic research conducted at this location has stimulated interest and cooperative interactions with industry for a full-scale commercialization effort. Utilization and applications research by both industry and the USDA-ARS National Agricultural Utilization Research Center (NCAUR), Peoria, Illinois have further accelerated the developmental effort. During the past three years, two companies have been working closely with this program to accelerate the commercialization process. Our joint efforts have provided funding support for commercialization from the USDA Alternative Agriculture Research and Commercialization (AARC) Center, and from the Department of Defense through the USDA-CSRS Office of Agricultural Materials for crop production systems research. Germplasm collection of lesquerella was supported partially through a grant from the USDA-ARS Plant Exploration Office. The objectives of this research are to collect, evaluate, and develop improved germplasm; to develop appropriate cultural and water management practices; and to assess the potential for full commercialization.

APPROACH: 1. Collect, evaluate, and enhance lesquerella germplasm for increased seed, seed oil, and hydroxyfatty acid yields; increase seed size and plant height; earlier flowering and seed set; and other improved plant growth characteristics by using appropriate breeding, genetic, and cytogenetic techniques.

2. Make appropriate genetic crosses; select, test, and develop high yielding cultivars or hybrids capable of full commercialization.

3. Develop and evaluate appropriate cultural and management systems, including planting rates and methods; water use, weed and pest management; seed production and harvesting methods.

4. Work cooperatively with private industry and other public research entities to increase basic and applied research, and to increase lesquerella seed for pilot plant oil extraction and evaluation, oil and meal utilization, and new product development for full commercialization.

FINDINGS: The first year of our major germplasm collection effort throughout the country was successfully started in April 1993, and continued to September 1993, in Arizona and New Mexico. Forty-nine new accessions of L. fendleri were collected in addition to 39 of ten other species including L. arizonica, L. cinerea, L. gordonii, L. intermedia, L. pinetorum, L. purpurea, L. rectipes, L. ovalifolia, and L. wardii. Additionally, one accession of Physaria floribunda and three of P. newberryi were collected.

The replicated yield trial of the half-sib families from the 56 selections (45 + 2 check lines @ 6 reps. and 15 observationals @ 2 reps. -- plots 1 x 5 m., 2 rows/bed) made for high oil and fatty acid yield was harvested in June, 1993. Twenty of the highest yielding lines were identified for recombination in three recurrent selection populations, which were planted in isolation on October 21, 1993, at MAC. These populations are designated LY-0 for high overall seed, oil and hydroxy fatty acid yield (13 lines); LO-0 for high seed oil yield (10 lines); and LH-0 for high hydroxy fatty acid yield (10 lines). Parent-offspring regressions will be calculated subsequently, and heritability parameters estimated for major yield factors. A major effort is being made to develop high yielding lines with autofertility, or the ability to set seed without cross pollination. We have determined that outcrossing rates in the field are as high as 89%. This was determined by measuring the gene frequency of five codominant loci from three isozyme systems within 20 randomly selected plants and their half-sib family progenies. The large numbers of progeny plants from field selected, putative autofertile plants grown in the greenhouse during the 1992-93 season did not yield any lines that showed a high degree of autofertility. Additional progeny plants will be grown in the greenhouse this winter for further evaluation without bagging, which may have had an adverse effect on seed set from self-pollination. The high frequency of male sterility we have observed to range from 6 to 8% in the field over a two-year period undoubtedly contributes to a high natural rate of cross pollination. It may also exert a significant constraint on the realization of high seed yields, especially in situations where the population of bees and other pollinating insects may be deficient. We are currently studying the inheritance of male sterility and F2 populations of crosses between male sterile and fertile plants. These data will help us determine how to manage male sterility in our breeding populations and may provide a mechanism for hybrid seed production.

Field research plots during the 1992-93 growing season included experiments to determine water use, dates and methods of planting, weed control, and nutritional requirements (results of these experiments are detailed in a separate report). An 8.1-ha (20-ac) pilot seed production field was planted in October 1992 on level basin fields at The University of Arizona Maricopa Agricultural Center (MAC). Combine-harvested yields were below 1,300 kg/ha, less than expected or desired. Much of the yield reduction is attributed to an excessively high seeding rate, which resulted in a plant population in excess of 1.6 million/ha. An independent University of Arizona graduate student research experiment conducted on one border of the field provides collaborative support to our conclusion. Manually thinned and harvested replicated plots ranged from 0.25 to 1.0 million plants/ha. Seed yields on the unthinned, control plots were essentially identical to those of the combine harvested yields on the whole field. Yields from about 1,400 to 1,500 kg/ha were obtained at plant densities of 0.75 to 1.0 million/ha, respectively. We conclude that optimum planting density with our currently available germplasm should be from 0.8 to 1.0 million/ha (325-400,000/ac). This equates to a seeding rate of 8-10kg/ha (7 to 9lb/ac) to obtain these optimal plant stands.

INTERPRETATION: The major role of USWCL research effort is to provide the lead in new germplasm collection and evaluation, genetic enhancement and improvement of germplasm, and the development of improved varieties or hybrids. The second role is to provide leadership and coordination in the development of a viable crop management system encompassing plant establishment, weed and pest control, water management, and mechanization. Continued research on water use efficiency and timing of water application is clearly needed. The preliminary results of the selection program for high oil and fatty acid yields are promising and are expected to yield positive results with an immediate target for developing new varieties with the capability of producing 2,250 kg/ha (2,000 lbs/ac) of seed with an oil content of 30%. The infusion of AARC Center funding into the project, the timely additional support of DOD funding for research and development of improved crop production and harvesting systems, and the active participation of industry are very positive indications that lesquerella will be commercialized successfully and speedily.

FUTURE PLANS: The three recurrent selection crossing block plantings made in October 1993 at MAC will be harvested in May or June 1994. A series of single plant selections will be made within each of the three crossing blocks. The 10-acre pilot planting for seed production and the plantings for the agronomic and water management experiments, which have been made in cooperation with Mr. John Nelson, will be discussed in a separate report. Special emphasis will be given to selection for autofertility in both the greenhouse and the field. The second year of the plant collection effort will be conducted from March to September 1994 within the targeted area of Texas and Oklahoma. Initial efforts will be made to incorporate molecular genetic techniques in our germplasm enhancement efforts.

COOPERATORS: J.M. Nelson, R.L. Roth, A.N. Mamood, J.C. Wade, and P.N. Wilson, Univ. Arizona, Tucson, AZ; J.H. Brown, J.D. Arquette, and K. Dwyer, International Flora Technologies, Apache Junction, AZ; K.A. Walker, B. Phipps, A. Hill, Mycogen Plant Sciences, San Diego, CA; E.H. Erickson, G.M. Loper, and A.N. Mamood, USDA-ARS, Carl Hayden Bee Research Laboratory, Tucson, AZ; M.A. Foster and J. Moore, Texas A&M, Fort Stockton and Pecos, TX; R.J. Roseberg, Oregon State Univ. Medford, OR; J.L. Fowler, New Mexico State Univ., Las Cruces, NM; H.L. Bhardwaj, Virginia State Univ. Petersburg, VA; R.Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL; L.D. Clements, and D.A. Kugler, USDA-CSRS-SPPS Office of Agricultural Materials, Washington, DC; L.K. Glaser, USDA-ERS, Washington, DC.

CULTURAL MANAGEMENT OF LESQUERELLA: WATER AND STRESS MANAGEMENT

D.J. Hunsaker, Agricultural Engineer; F.S. Nakayama, Research Chemist
D.A. Dierig, Research Geneticist; A.E. Thompson, Research Geneticist; and W.L. Alexander, Agronomist

PROBLEM: Prior research has indicated that the seasonal water requirement of lesquerella is on the order of 600 mm. However, little is known about the response of the crop to water application during various stages of growth, particularly over the flowering and fruit maturation stages. Such information is necessary before definitive guidelines on irrigation scheduling can be made. The objective of this research is to determine the water use and water-stress behavior of lesquerella under various irrigation regimes. This effort investigated the effects of supplemental winter irrigation, irrigation frequency, and limited irrigation on the yield of lesquerella.

APPROACH: The 1992-93 lesquerella crop was planted in 1.0-m raised beds on October 1, 1992, at the Maricopa Agricultural Center. This followed the incorporation of ammonium phosphate (16:20) in the field, which was applied at a rate of 335 kg ha^{-1}. Crop establishment was accomplished by several flood irrigations following planting totaling 200 mm. The 0.4-ha site was divided into 40 plots, each 7 rows wide and 12.5 m in length. Eight irrigation treatments were randomly assigned to the plots. There were five replications.

The irrigation treatments were as follows:

Well-Watered Treatments

Treatment 1 (T1) - irrigated weekly, plus two supplemental irrigations in winter.
Treatment 2 (T2) - irrigated weekly.
Treatment 3 (T3) - irrigated biweekly, plus two supplemental irrigations in winter.
Treatment 4 (T4) - irrigated biweekly.

Limited-Water Treatments

Treatment 5 (T5) - irrigated biweekly beginning after 10% flower (~mid-March.)
Treatment 6 (T6) - irrigated biweekly, except during 10-50% flower (~mid-March through early April).
Treatment 7 (T7) - irrigated biweekly, except during 50-100% flower (~late-March through mid-April).
Treatment 8 (T8) - irrigated biweekly, except during seed pod formation (~mid-April through harvest).

Regular irrigation commenced on February 19, 1993, and ended on May 5, 1993. Supplemental irrigation was applied to T1 and T3 plots on December 3, 1992, and February 4, 1993, to promote early growth. One neutron access tube was placed in the center of each plot to a depth of 2.0 m, and the soil water content was monitored throughout the growing season. Soil water depletion over a soil depth of 1.1 m was used to estimate evapotranspiration (ET). Two 1.0-m^2 subplots were hand-harvested in all replicates on June 3, 1993. Total aboveground plant dry weights were determined before hand-threshing the seed for yield measurement. Seed weight (weight per 100 seeds) and seed oil content also were determined.

FINDINGS: Precipitation was unusually high during the 1992-93 experiment (190 mm between planting and harvest). Most rainfall (160 mm) occurred between December 1, 1992, and March 1, 1993, while about 25 mm of rainfall occurred at the end of March. Consequently, the amount of total water applied (Table 1) was considerably higher in the well-watered treatments (T1-T4) than that needed to meet the seasonal water requirement of lesquerella (~600 mm as indicated from prior research). Even limited-water treatments (T5-T8) received 710-770 mm of water during the season. However, less than half of the total water of treatments T5-T8 was applied between March-May.

Seasonal ET varied from 620-685 mm over well-watered treatments (Table 1). As shown in Figure 1a, the differences in the seasonal ET that were found between well-watered treatments were mostly accounted for early in the season (January through February 1993), where T1 and T3 (supplemental irrigation) had higher ET than either T2 or T4. Seasonal ET varied from 545-600 mm over limited-water treatments (T5-T8), with the lowest ET in T8. In all limited-water treatments there was an indication of decreased ET during periods when irrigation was withheld (Fig. 1b); during early March for T5, early April for T6, late April for T7, and the entire month of May for T8.

Analysis of harvest data indicated very little statistical differences among treatments (Table 2). Plant dry weight was significantly higher in treatments T3 and T7 than T8 and T2. Seed yields were lower than expected for the well-watered treatments and ranged from 800-890 kg ha^{-1}. Seed yield differences among well-watered treatments were not significant. The lowest yields were obtained in T6 (irrigation withheld between March 13 through April 12) and T8 (irrigation withheld after 12 April). However, these treatments were not significantly different than other treatments with the exception of T3 (Table 2). Little or no differences were found between treatments in seed weight or seed oil content.

INTERPRETATION: The effects of supplemental winter irrigation and irrigation frequency on the yield of lesquerella in the 1993 harvest year were generally small, but they may have been masked by frequent seasonal precipitation. Higher rates of ET during January and February for treatments receiving supplemental irrigation indicate increased soil evaporation early in the growing season before the lesquerella crop had attained full cover. Under well-watered conditions, seed yield was the same under biweekly irrigation as under weekly. This result was different than that in a study conducted in the 1990 harvest year, which attained greater seed yield under a lower irrigation frequency compared to a higher irrigation frequency. Lower plant biomass in weekly compared to biweekly irrigation suggests a possible reduction in fertility caused by nutrients leached from the root zone under the more frequent irrigation regime. Although high frequency irrigation would be less preferable in farm management practices, additional information on nutrient management under both irrigation regimes is required before a positive explanation of yield response to irrigation frequency can be made.

Withholding irrigation during different growth stages produced an apparent reduction in water use until irrigation was resumed. However, the impact on seed yield was small relative to well-watered conditions. Irrigation withheld during mid-flower and seed pod formation appeared to have had a larger effect on seed yield than when irrigation was withheld during early and late flower. However, the effects of water stress during early and late flower may have been reduced because of significant precipitation that occurred in February and at the end of March.

FUTURE PLANS: Research on lesquerella irrigation and stress management will continue in the 1993-1994 growing season. A field experiment will be conducted to explore the interaction of water and fertilizer application on seed yield response.

COOPERATORS: J. Nelson, Agronomist, The University of Arizona Maricopa Agricultural Center.

Table 1. Total water applied and estimated seasonal evapotranspiration for irrigation treatments in 1992-1993.

Irrigation Treatment	Number of Irrigations[1]	Total Water Applied[2] (mm)	Seasonal Evapotranspiration[3] (mm)
1	14	1050	685
2	12	930	650
3	9	950	680
4	7	830	620
5	5	710	560
6	6	750	600
7	6	770	580
8	5	710	545

[1] Does not include irrigations given for crop establishment.
[2] Includes 200 mm of irrigation for crop establishment plus 190 mm of rainfall.
[3] Estimated from soil water balance over a 1.1-m soil depth between November 3, 1992, through May 27, 1993.

Table 2. Seed yield and yield components for irrigation treatments in 1992-1993.

Irrigation Treatment	Plant Dry Weight (kg/a)	Seed Yield (kg/ha)	Seed Weight (g/100)	Seed Oil Content (%)
1	6580^{ab}	820^{ab}	0.056^{a}	24.2^{ab}
2	6130^{b}	820^{ab}	0.048^{bc}	24.1^{ab}
3	7020^{a}	890^{a}	0.055^{a}	23.8^{ab}
4	6810^{ab}	800^{ab}	0.059^{a}	24.1^{ab}
5	6240^{ab}	780^{ab}	0.057^{a}	24.6^{a}
6	6880^{ab}	750^{b}	0.052^{a}	23.6^{b}
7	6980^{a}	810^{ab}	0.055^{a}	24.2^{ab}
8	6040^{b}	740^{b}	0.048^{a}	24.0^{ab}

[abc] Means followed by different letters in a column are significantly different at the 95% probability level.

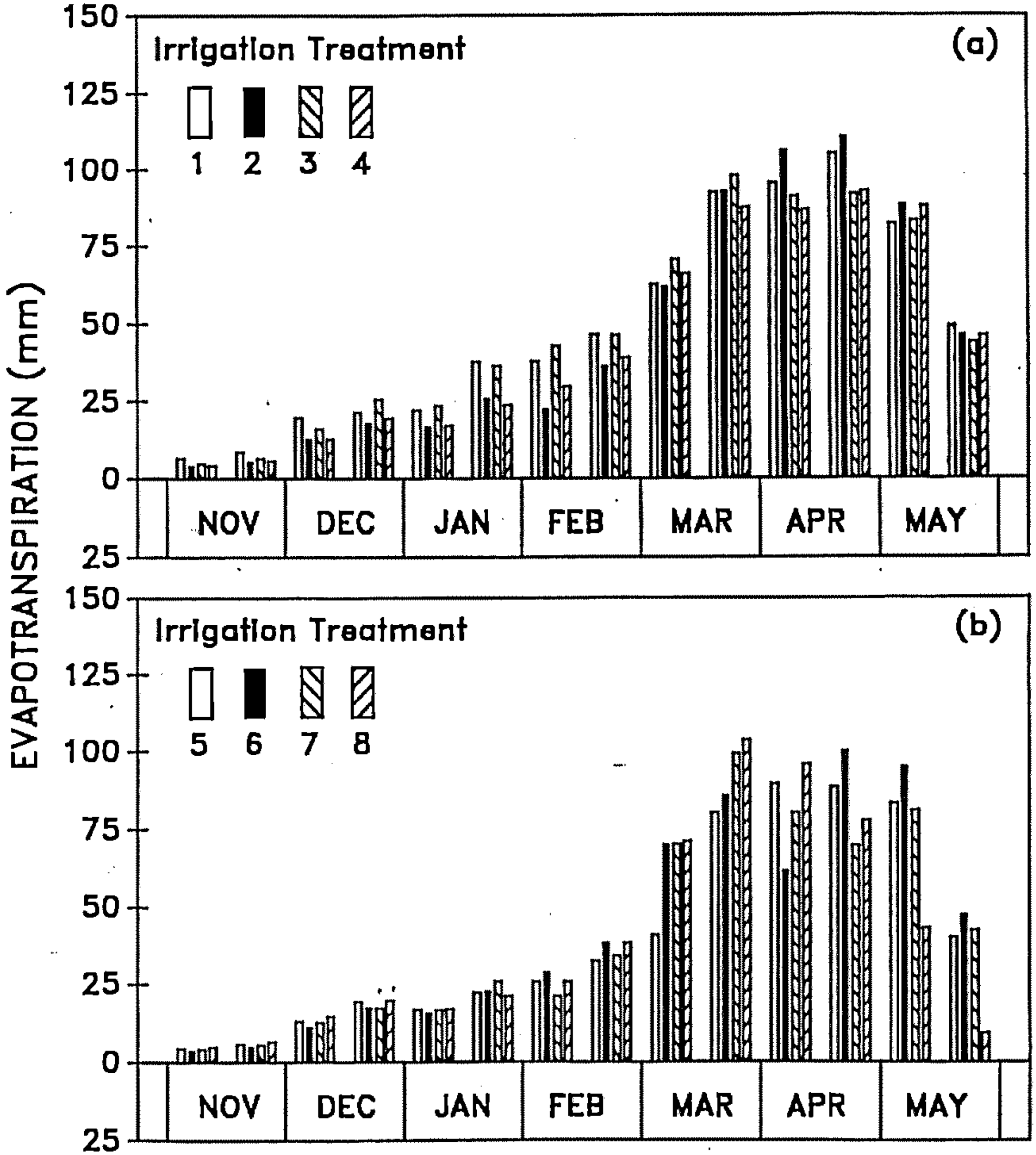

Figure 1. Semimonthly evapotranspiration for irrigation treatments in the 1992-1993 lesquerella experiment.

GERMPLASM IMPROVEMENT OF VERNONIA

A.E. Thompson, Research Geneticist; D.A. Dierig, Research Geneticist; and
F.S. Nakayama, Research Chemist

PROBLEM: To date, no oilseed crop contains natural epoxidized oils that can be utilized by industry. Vernonia galamensis produces seed oil with high quantities of epoxy fatty acids (EFA). These oils can be used to produce paints and coatings with low or no volatile organic compounds (VOC), thermoset resins and coatings, polymer blends, dibasic acids, adhesives, natural epoxy composite materials, and cosmetics. Only a few plants have been found to contain naturally occurring epoxy oils, but vernonia has the highest potential for commercialization. Until recently, all available Vernonia galamensis germplasm, which is native to equatorial Africa, required short day photoinduction for flowering and subsequent seed production. This prevented successful culture of vernonia within the continental U.S. However, we have successfully utilized one accession of subspecies galamensis var. petitiana, which is day-neutral and will flower any time of the year in Arizona and at other latitudes in the U.S., to produce new hybrid germplasm. The objective of this research is to develop high yielding germplasm and cultivars with adaptation to the U.S. through hybridization and selection and to evaluate vernonia's potential for full commercialization as a new industrial oilseed crop.

APPROACH: 1. Evaluate and enhance germplasm of vernonia for high seed oil yield and fatty acid content; day neutral flowering; autofertility; vigorous seed germination, emergence, and seedling growth; and good mature seed retention using appropriate breeding, genetic, and cytogenetic techniques.

2. Make appropriate genetic crosses; select, test, and develop high yielding cultivars capable of full commercialization.

3. Develop and evaluate cultural and water management systems.

4. Work cooperatively with private industry and other public research entities to expedite full commercialization.

FINDINGS: Seeds from the F_1s and F_2 selections made in Arizona and additional selections made at different locations by cooperating scientists were analyzed for seed oil and vernolic acid contents at the USDA-ARS National Center for Agricultural Utilization Research (NCAUR), Peoria, Illinois. F_3 progeny plants from crosses involving A399 (V029, subsp. galamensis var. petitiana) as the female parent with A382 (V001, subsp. galamensis var. ethiopica); A388 and A389 (V003 & V004, subsp. galamensis var. galamensis); A437 (V013, unclassified as to subspecies and variety); and A390 (V018, subsp. mutomensis) were grown at The University of Arizona Maricopa Agricultural Center (MAC) for evaluation and further selection. On March 16, 1993, a total of 100 seeds from each F_3 population were germinated in seed flats in the greenhouse to determine rate of germination and apparent seed dormancy. About 2,800 F_3 seedling plants were transferred to flats for subsequent transplanting into the field on May 12, 1993. Of the 106 F_3 populations planted, 28 of the F_2 selections were made by cooperators in Texas, 11 from Oregon, and 4 from Iowa. A total of 72 single plants selections were made from the total population. The numbers selected from each type of cross are: A399 x A382 -- 56; A399 x A388 -- 3; A399 x A389 -- 3; A399 x A437 -- 7; and A399 x A390 -- 3. Thirty-four of the F_3 selections were selected and planted in isolated plots on October 6, 1993, for seed increase at the USDA-ARS Winter Nursery at Isabella, Puerto Rico.

Remnant seeds of 22 selected F_2s were planted in the greenhouse on August 25, 1993, for classification of their flowering response. A total of over 1,100 plants are being grown under supplimental lights and are currently being classified to determine the genetic basis for flowering under long daylength conditions. About 75% of the field grown F_2 plants in 1992 flowered, which indicates that the flowering response may be under single gene control. However, we have observed that considerable variation exists in the number of days after planting for flowering to occur, both within and between individual hybrid populations This would indicate that quantitative genetic factors may play an important role in the flowering response.

A network of cooperating scientists from USDA-ARS, State Agricultural Experiment Stations, and industry in Oregon, Idaho, Missouri, Virginia, Georgia, Louisiana, Oklahoma, Texas, and New Mexico cooperatively evaluated a selected portion (26) of the F_3 populations. The cooperators had varying success with the plantings. Some direct seeded into the field while others grew the plants in greenhouses and transplanted into the field. Complete details of the 1993 cooperators' results are not yet available. Analysis of seed oil and fatty acid contents of uniform seed lots of A399, var. petitiana, grown in 1992 at six locations (Arizona, Iowa, Louisiana, Oregon, Texas, and Virginia) indicated that environmental effects significantly altered chemical composition. Oil contents ranged from 36.1% in Oregon to 41.8% in Virginia, and the content in Arizona was 37.0%. The vernolic acid (18:1 epoxy) contents ranged from a low of 61.8% in Arizona to 78.7% in Virginia. In Arizona, the seed weight in g/1000 was 2.20g, and the range was from 2.10g in Texas to 2.75g in Oregon.

INTERPRETATION: The genetic segregation and performance of the various F_3 populations in Arizona and the various locations throughout the country were very encouraging. It is now obvious that the day neutral flowering response of var. petitiana (A399) can be transferred successfully by conventional hybridization with other subspecies and varieties. The excellent flowering response under the long daylength growing conditions in Oregon and other locations provides very strong verification of the successful genetic transfer of day neutral flowering since these plantings were made by direct seeding in the field at a time when the natural daylength was about 14 hours. It has been demonstrated fully that selection within the segregating F_2 and F_3 populations can isolate new genetic recombinations with such desirable characters as flowering under long daylengths, determinate flowering and concentrated seed set, lack of seed dormancy and vigorous seedling growth, autofertility, and possibly good mature seed retention and tolerance to soilborne pathogens. We have concluded that full-scale development of vernonia as a new industrial oilseed crop for production in various geographical areas throughout the U.S. is attainable and should be pursued vigorously.

FUTURE PLANS: On the basis of our promising results, we were awarded financial support from the Department of Defense through the USDA-CSRS Office of Agricultural Materials. These funds are being utilized to accelerate the enhancement of germplasm, the increase of seed of selected lines in the Winter Nursery in Puerto Rico, and the support of research activity of our cooperating network throughout the country. If we are successful in increasing sufficient seeds of the F_4 lines, seeds will be made available to our cooperators for further evaluation and selection and for the initiation of crop production systems research. Seeds from the selected F_3 plants and from the F_4 seed increase in Puerto Rico will be grown in research plots at MAC for further evaluation and selection. Selection for favorable genetic combinations of seed and oil yield, and desirable plant growth characters, as practiced during the past year will be continued. Cooperative research in cytogenetics and molecular genetics will be initiated with the University of Arizona under an existing specific cooperative agreement. Pulsed NMR equipment is being purchased to initiate on-site nondestructive seed oil analysis for our and our cooperators' selections and research plot samples. Research on developing appropriate cultural and water management systems is planned for initiation in 1994.

COOPERATORS: R. Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL; W.W. Roath, USDA-ARS-NCRPIS, Ames, IA; C.L. Webber III, USDA-ARS-SCARL, Lane, OK; A.L. Urie and S. Gortsema, USDA-ARS-PWA, Aberdeen, ID; M.A. Foster, Texas A&M Expt. Station, Fort Stockton, TX; R.J. Roseberg, Oregon State Univ., Medford, OR; H.L. Bhardwaj, A.I. Mohamed, M.E. Kraemer, and M. Rangappa, Virginia State Univ. Petersburg, VA; C.W. Kennedy, Louisiana State Univ. Baton Rouge, LA; S.C. Phatak, Georgia Coastal Plains Expt. Station, Tifton, GA; J.M. Nelson, Univ. Arizona MAC, Maricopa, AZ; D.T. Ray and A.N. Mamood, Univ. of Arizona, Tucson, AZ; R.L. Myers, Univ. Missouri, Columbia, MO; J.L. Fowler, New Mexico State Univ., Las Cruces, NM; J.H. Brown and J.D. Arquette, International Flora Technologies, Apache Junction, AZ.

ELECTRONICS ENGINEERING LABORATORY

D. E. Pettit, Electronics Engineer

The Electronics Engineering Laboratory is staffed by an Electronics Engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase and upgrade of electronic equipment.

Support provided to research in 1993 included

- Researching for a modification and design to add an auto reset capability to the laboratory Power Management System. This system provides regulated power for the Uninterruptable Power Supply System (UPS) supplying AC power to the Local Area Network (LAN) server computer and various other support computer systems.

- Design and construction of a 16-channel switch box unit interfaced to Omnidata's EZ Logger data collection unit to control multiple valves in test (see Hunsaker, Clemmens, and Alexander, "High-Frequency, Small Volume Level Basin Irrigation for Cotton," p. 12 in this report).

- Design and construction of a combination discriminator, amplifier to interface Replogle and Wahlin's propeller speed sensor to an Omnidata EZ Logger data collection unit (see Replogle and Wahlin, "Irrigation Flow Measurement Studies," p. 9 in this report).

- Interface and program for setup of Bartex Aquatrak Depth Sensor evaluation (see Replogle and Wahlin, "Irrigation Flow Measurement Studies," p. 9 in this report).

- Modification of 150 units of watch clocks for advance water delivery timing (see Hunsaker, Clemmens, and Alexander, "High-Frequency, Small Volume Level Basin Irrigation for Cotton," p. 12 in this report).

- Modification of high resolution computer video cards.

- Modification of design for SPAD hand-held leaf evaluation unit, replacing the interface cable, which tended to break, with a swiveling head, multiple connection plug that was easily exchanged (see Rice, et al., "Nitrogen Fertilizer and Water Transport under 100% Irrigation Efficiency, p. 41 in this report).

- Design and construction of a radio frequency FM short-range transmitter system to a laboratory greenhouse to monitor phone page responses.

Repairs and recalibrations in 1993 included multiple IRT hand-held and field stationary units, an HP Integrator, CO_2 Analyzers, laptop computer LCD backlight, centrifuge temperature control unit, field anemometers, 8-band channel radiometer, and the MAC Farm data collection trailer security alarm.

COMPUTER FACILITY

T. A. Mills, Computer Specialist

The computer Facility is staffed by one full-time Computer Specialist (Terry Mills) and one Computer Assistant (Harold Mastin). Support is provided to all Laboratory and Location Administration Office computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory's Local Area Network (LAN), computers, and peripherals. The LAN utilizes six 10Base-T hubs with a standard Ethernet backbone to connect six Laboratory buildings. Systems include a SUN Sparc Station II and over 50 personal computers. The network is currently supporting NOVELL Netware 3.11, SunMicro UNIX 4.1, OS/2, and DOS. Remote asynchronous communications are provided by a Netware Access Server, a Netware Asynchronous Communications Server, and a 56kbs lease line gateway to Arizona State University (ASU). Through ASU and WESTNET, our LAN is connected to the INTERNET. The Laboratory has an Internet Class C IP address and operates under the fully qualified domain uswcl.ars.ag.gov.

Expanding the Laboratory network was the primary focus in 1993. Asynchronous communications were provided by six modems, allowing access to and from the network. In addition, ASU agreed to provide us with a gateway connection to the WESTNET network, giving the Laboratory worldwide access through the INTERNET. The UNIX network server provides MAIL, TELNET, and FTP services to and from the INTERNET. A NOVELL Netware 3.11 File Server is being used for LAN file services and local mail.

Plans for 1994 will focus on better integration between the UNIX and Netware servers. A third file server is planned to provide Network File Services to both the current servers. Also proposed is the addition of a mail interface to integrate the Netware and UNIX mail systems.

LIBRARY AND PUBLICATIONS

L. S. Seay, Publications Clerk

Library and publications functions, performed by one Publications Clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers,[1] as well as for holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 1600 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U. S. Water Conservation Laboratory List of Publications, containing almost 1800 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications. Publication lists and most of the publications are available on request.

Compilation of an Auxiliary Laboratory Publications List is nearing completion. The Auxiliary List will include selected reports and non-peer-reviewed material to facilitate wider dissemination and use.

An automated system for journal holdings is being developed.

[1] Appendix A lists manuscripts published or formally accepted for publication in 1993. Appendix B lists separately those manuscripts published as special issues or projects in 1993.

MACHINE SHOP

C. L. Lewis, Machinist

The machine shop, staffed by one full-time and one part-time machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U. S. Water Conservation Laboratory research projects. Following are examples of work orders completed in 1993:

A root core sample tube was fabricated to obtain samples for root biomass measurements to study effects of elevated CO_2 levels on root growth and for soil chemical analysis as part of the FACE project The tube is 1.500 meters tall with a 4.250" OD and a 3.750" ID. It is fabricated from 304 stainless steel and has a removable cross-section port and a removable drive unit (see Kimball, et al., "Progress and Plans for the Free-Air CO_2 Enrichment [FACE] Project," p. 63 in this report).

A chamber was fabricated for a flow measurement device being developed to test the rising air float technique. The chamber is constructed from two 55-gallon steel drums with a removable 61" x 18.500" plexiglass view port (see Replogle and Wahlin, "Irrigation Flow Measurement Studies," p. 9 in this report).

Thirty-two chambers were fabricated for soil CO_2 flux sampling. The chambers are constructed from 8"-diameter PVC tubing in two interlocking sections with plexiglass covers (see Nakayama, "Soil Gas Fluxes in CO_2-Enriched Wheat," p. 68 in this report.

APPENDIX A

Manuscripts Published or Accepted in 1993

1. AKIN, D.E., B.A. KIMBALL, J.,R. MAUNEY, R.L. LAMORTE, G.R. HENDREY, K.F. LEWIN, J. NAGY, and R.N. GATES. Influence of enhanced CO_2 concentration and irrigation on sudangrass digestibility. Agric. and Forest Meteorology. WCL# 1756. (ACCEPTED-11 FEB 1993). 5344-11000-005-00D.

2. AL-AZBA, A., and T. STRELKOFF. Correct form of Hall Technique for border irrigation advance. J. Irrig. and Drain. Eng. WCL# 1689. (ACCEPTED-24 MAR 1993. 5344-13000-005-00D.

3. ALLEN, R.G., G.L. DICKEY, J.L. WRIGHT, J.F. STONE, and D.J. HUNSAKER. Error analysis of bulk density measurements for neutron gauge calibration. IN: 1993 Nat. Conf. on Irrig. and Drain. Eng., ASCE, Park City, UT. 21-23 Jul 1993. WCL# 1762. (ACCEPTED-06 Aug 1993). 5368-13000-003-00D.

4. BATCHILY, A.K., A.R. HUETE, M.S. MORAN, and H. LIU. 1993. Variation of vegetation indices derived from multi-temporal TM images Unpaginated. IN: Proc. of the Pecora Conf., Sioux Falls, ID. 24-26 Aug 1993. WCL# 1742. 5344-13660-001-00D.

5. BHATTACHARYA, N.C., J.W. RADIN, B.A. KIMBALL, J.R. MAUNEY, G.R. HENDREY, J.L. WRIGHT, K.F. NAGY, and D.C. PONCE. Diurnal changes in leaf water potential and stomatal conductance in cotton under optimal and limiting water levels in a free-air CO_2 enriched environment. Agric. and Forest Megeorology. WCL# 1757. (ACCEPTED-18 FEB 1993). 5344-11000-004-01R.

6. BOUWER, H. 1992. Aquifer recharge with wastewater. FAO of the United Nations I&D Paper No. 47, Wastewater Treatment and Use in Agriculture. p. 43-50. WCL# 1294. 5422-20790-005.

7. BOUWER, H. 1992. Artificial recharge of groundwater. p. 159-166. IN: Joseph B. Summers (ed.) Irrig. and Water Resources in the 1990's. U. S. Committee on Irrig. and Drain. Proc. 1992 Nat. Conf. 5-7 Oct 1992. WCL# 1729. 5344-13000-003-00D.

8. BOUWER, H. 1993. From sewage farm to zero discharge. European Water Pollution Control. 3(1):9-16. WCL# 1715. 5344-13000-003-00D.

9. BOUWER, H. 1993. From sewage farm to zero discharge. p. 719-732. IN: Proc. of Conservation 1993, The New Water Agenda, Sessions W3-1 through 4A-6. Las Vegas, NV. 12-16 Dec 1993. WCL# 1738. 5344-13000-003-00D.

10. BOUWER, H. 1993. Resolving competition between urban and agricultural water use. p. 1429-1437. IN: Proc. 15th Congress on Irrig, and Drain., Water Management in the Next Century. 1993. The Hague, The Netherlands. WCL# 1749. 5344-13000-003-00D.

11. BOUWER, H. 1993. Urban and agricultural competition for water, and water reuse. p. 79-84. IN: Richard G,. Allen (ed.) Proc. Management of Irrig. and Drain. Systems Integrated Perspectives. WCL# 1733. 5344-13000-003-00D.

12. BOUWER, H. 1993. Urban and agricultural competition for water and water reuse. Int. J. of Water Resources Dev. 9(1):13-25. WCL# 1728. 5344-13000-003-00D.

13. CLEMMENS, A.J., M.G. BOS, and J.A. REPLOGLE. 1993. 123 pp. IN: A.J. Clemmens, M.G. Bos, and J.A. Replogle (eds.) FLUME: Design and Calibration of Long-throated Measuring Flumes. Version 3.0. Publication #54. International Institute for Land Reclamation and Improvement/ILRI, P.O. Box 45, 6700 AA Wageningen, The Netherlands. WCL# 1751. 5344-13000-005-00D.

14. CLEMMENS, A.J., M.G. BOS, and J.A. REPLOGLE. 1993. Flume 3.0: A computer program for designing flumes and wiers. p. 867-874. IN: Agricultural Engineering Proc. ASCE Nat. Conf. on Irrig. and Drain., Park City, UT. 21-23 Jul 1993. WCL# 1722. 5344-13000-005-00D.

15. CLEMMENS, A.J., A.R. DEDRICK, and R.J. STRAND. 1993. Basin 2.0 for the design of level-basin irrigation systems. p. 875-882. IN: Proc. ASCE Nat. Conf. on Irrig. and Drain., Park City, UT. 21-23 Jul 1993. WCL# 1724. 5344-13000-005-00D.

16. DESOUSA, P.L., A.R. DEDRICK, A.J. CLEMMENS, and L.S. PEREIRA. 1993. Benefits and costs of laser-controlled leveling--a case study. p. 1237-1247. IN: Proc. 15th Int. Congress on I&D, Water Management in the Next Century, The Hague, The Netherlands, 6-11 Sep 1993. WCL# 1736. 5344-13000-005-00D.

17. DICKEY, G.L., R.G. ALLEN, J.L. WRIGHT, N.R. MURRAY, J.F. STONE, and D.J. HUNSAKER. Soil bulk density sampling for neutron probe calibration. 1993 Nat. Conf. Irrig. and Drain. Eng., ASCE, Park City, UT. 21-23 Jul 1993. WCL# 1761. (ACCEPTED-06 Apr 1993). 5368-13000-003-00D.

18. DIERIG, D.A., and A.E. THOMPSON. 1993. Vernonia and lesquerella potential for commercialization. p. 362-367. IN: J. Janick and J.E. Simon. (ed.) New Crops. John Wiley and Sons, Inc. New York, NY. WCL# 1640. 5344-21410-001-00D.

19. DIERIG, D. A., A.E. THOMPSON, and F.S. NAKAYAMA. 1992. Lesquerella commercialization efforts in the United States. Industrial Crops and Products. 1:289-293. WCL# 1686. 5344-21410-001-00D.

20. DUGAS, W.A., M.L. HEUER, D.J. HUNSAKER, B.A. KIMBALL, K.F. LEWIN, J. NAGY, and M. JOHNSON. Sap flow measurements of transpiration from cotton growth under ambient and enriched CO_2 concentrations. WCL# 1682. (ACCEPTED-16 Sep 1993). 5344-11000-005-00D.

21. GARCIA, R.L., S.B. IDSO, and B.A. KIMBALL. Net photosynthesis as a function of carbon dioxide concentration in pine trees grown at ambient and elevated CO_2. Environ. Exp. Bot. WCL# 1714. (ACCEPTED-DEC 1993). 5344-11000-005-00D.

22. GARCIA, R.L., S.B. IDSO, G.W. WALL, and B.A. KIMBALL. Changes in net photosynthesis and growth of pinus eldarica seedlings in response to atmospheric CO_2 enrichment. J. Plant Cell and Environ. WCL# 1713. (ACCEPTED-DEC 1993). 5344-11000-005-00D.

23. GELLMAN, D.I., S.F. BIGGAR, M.C. DINGUIRARD, P. HENRY, M.S. MORAN, K.J. THOME, and P.N. SLATER. 1993. Review of SPOT-1 and -2 calibration at White Sands from launch to the present. p. 118-125. IN: Proc. SPIE Int. Symp. on Optical Eng. and Photonics in Aerospace and Remote Sensing, Orlando, FL. 12-16 Apr 1993. WCL# 1726. 5344-13660-001-00D.

24. GRAYBILL, D.A., and S.B. IDSO. 1993. Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies. Global Biogeochemical Cycles. 7(1):81-95. WCL# 1660. 5344-11000-005-00D.

25. GRIES, C., B.A. KIMBALL, and S.B. IDSO. Nutrient uptake during the course of a year by sour orange trees growing in ambient and elevated atmospheric carbon dioxide concentrations. J. Plant Nutrition. 16:(1):129-147. WCL# 1651. 5344-11000-004-00D.

26. HATFIELD, J.L., and P.J. PINTER, JR. 1993. Remote sensing for crop protection. Crop Protection. 12(6):403-414. WCL# 1657. 3625-12000-002-00D.

27. HENDREY, G.R., and B.A. KIMBALL. The FACE Program. Agric. and Forest Meteorology. WCL# 1684. (ACCEPTED-01 FEB 1993). 5344-11000-004-00D.

28. HUMES, K.S., W.P. KUSTAS, T.J. JACKSON, T.J. SCHMUGGE and M.S. MORAN. 1993. Combined use of optical and microwave remotely sensed data for the estimation of surface energy balance components over a semi-arid watershed. p. 86-89. IN: Proc. of IEEE Topical Symp. on Combined Optical-Microwave Earth and Atmosphere Sensing, Albuquerque, NM. 22-25 Mar 1993. WCL# 1721. 1270-13610-002-00D.

29. HUMES, K.S., W.P. KUSTAS, and M.S. MORAN. Use of remote sensing and reference site measurements to estimate instantaneous surface energy balance components over a semi-arid rangeland watershed. Water Resources Res. WCL# 1701. (ACCEPTED-MAY 1993). 1270-13610-002-00D.

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31. HUNSAKER, D.J., G.R. HENDREY, B.A. KIMBALL, K.F. LEWIN, J.,R. MAUNEY, and J. NAGY. Cotton evapotranspiration under field conditions with CO_2 enrichment and variable soil moisture regimes. Agric. and Forest Meteorology. WCL# 1680. (ACCEPTED-MAY 1993). 5344-13000-005-00D.

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33. IDSO, K.E., and S.B. IDSO. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: A review of the past ten years research. Agric. and Forest Meteorology. WCL# 1718. (ACCEPTED-NOV 1993). 5344-11000-005-00D.

34. IDSO, S.B., and B.A. KIMBALL. 1993. Effects of atmospheric CO_2 enrichment on net photosynthesis and dark respiration rates of three Australian tree species. J. Plant Physiol. 141:166-171. WCL# 1635. 5344-11000-004-01R.

35. IDSO, S.B., and B.A. KIMBALL. Effects of atmospheric CO_2 enrichment on the regrowth of sour orange trees after coppicing. Am. J. of Botany. WCL# 1739. (ACCEPTED-NOV 1993). 5344-11000-005-00D.

36. IDSO, S.B., and B.A. KIMBALL. 1993. Tree growth in carbon dioxide enriched air and its implications for global carbon cycling and maximum levels of atmospheric CO_2. Global Biogeochemical Cycles. 7(3):537-555. WCL# 1650. 5344-11000-005-00D.

37. IDSO, S.B., B.A. KIMBALL, D.E. AKIN, and J. KRIDLER. 1993. A general relationship between CO_2-induced reductions in stomatal conductance and concomitant increases in foliage temperature. Environ. Exp. Bot. 33:443-446. WCL# 1575. 5344-11000-005-00D.

38. IDSO, S.B., B.A. KIMBALL, and D.L. HENDRIX. 1993. Air temperature modifies the size-enhancing effect of atmospheric CO_2 enrichment on sour orange tree leaves. Environ. Exp. Bot. 33:293-299. WCL# 1663. 5344-11000-005-00D.

39. IDSO, S. B., B.A. KIMBALL, G.W. WALL, R.L. GARCIA, R.L. LAMORTE, P.J. PINTER, JR., J,R, MAUNEY, G.R. HENDREY, K.F. LEWIN, and J. NAGY. Effects of atmospheric CO_2 enrichment on the light response curve of net photosynthesis in cotton leaves. Agric. and Forest Meteorology. WCL# 1671. (ACCEPTED-MAY 1993). 5344-13660-001-00D.

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41. INOUE, Y., M.S. MORAN, and P.J. PINTER, JR. Remote Sensing of potential and actual daily transpiration of plant canopies using spectral vegetation index and stress index-concept with preliminary test. Japanese J. Agric. and Forest Meteorology. WCL# 1766. 5344-13660-001-00D.

42. JAYNES, D.B., and R.C. RICE. 1993. Transport of solute as affected by irrigation method. Soil Sci. Soc. Am. 57(5):1348-1353. WCL# 1658. 0500-00026-006-00D.

43. KIMBALL, B.A. 1993. Ecology of crops in changing CO_2 concentration. Japan J. of Agric. Meteorology. 48(5):559-566. WCL# 1692. 5344-11000-005-00D.

44. KIMBALL, B.A., R.L. LAMORTE, R.S. SEAY, P.J. PINTER, JR., R. ROKEY, D.J. HUNSAKER, W.A. DUGAS, M.L. HEUER, J.R. MAUNEY, and G.R. HENDREY. Effects of free-air CO_2 enrichment on energy balance and evapotranspiration. Agric. and Forest Meteorology. WCL# 1683. (ACCEPTED-MAY 1993). 5344-11000-005-00D.

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46. KIMBALL, B.A., J.R. MAUNEY, F.S. NAKAYAMA, and S.B. IDSO. 1993. Effects of elevated CO_2 and climate variables on plants. J. Soil and Water Conserv. 48(1):9-14. WCL# 1611. 5344-11000-005-00D.

47. KUSTAS, W.P., M.S. MORAN, K.S. HUMES, L.E. HIPPS, D.I. STANNARD, D.C. GOODRICH, E. SWIATEK, M. WELTZ, and J.H. BLANFORD. Evapotranspiration estimates at local and regional scales using optical remote sensing data collected from an aircraft platform over semiarid rangelands. Water Resource Res. WCL# 1698. (ACCEPTED-MAY 1993). 1270-13610-002-00D.

48. KUSTAS, W.P., E.M. PERRY, P.C. DORAISWAMY, and M.S. MORAN. Using satellite remote sensing to extrapolate evapotranspiration estimates in time and space over a semiarid rangeland basin. Remote Sens. of Environ. WCL# 1765. (ACCEPTED-DEC 1993). 5344-13660-001-00D.

49. KUSTAS, W.P., T.J. SCHMUGGE, K.S. HUMES, T.J. JACKSON, R. PARRY, M.A. WELTZ, and M.S. MORAN. 1993. Relationship between evaporative fraction and remotely sensed vegetation index and microwave brightness temperature for semi-arid rangelands. J. Appl. Meteorology. 32:1781-1790. WCL# 1767. 5344-13660-001-00D.

50. LEAVITT, S.W., E.A. PAUL, B.A. KIMBALL, and G.R. HENDREY. 1992. Isotopic estimation of inputs of carbon to cotton soils under FACE CO_2 enrichment. 4 pp. IN: Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge Nat. Lab. DOE Research Summary. WCL# 1664. 5344-11000-005-00D.

51. LEAVITT, S.W., E.A. PAUL, B.A. KIMBALL, G.R. HENDREY, J.R. MAUNEY, R. RAUSCHKOLB, H. ROGERS, K.F. LEWIN, P.J. PINTER, JR., and H.B. JOHNSON. Carbon isotope dynamics of CO_2-enriched systems. Agric. and Forest Meteorology. WCL# 1758. (ACCEPTED-20 FEB 1993). 5344-11000-004-00D.

52. MAAS, S.J., M.S. MORAN, and R.D. JACKSON. 1992. Combining remote sensing and modeling for Regional Resource Monitoring Part II: A simple model for estimating surface evaporation and biomass production. p. 225-234. IN: ASPRS/ACSM/TR'92 Convention: Mapping and Monitoring Global Change, Washington, DC. 3-8 Aug 1992. WCL# 1702. 5303-13210-002-00D.

53. MAAS, S.J., M.S. MORAN, M.A. WELZ, and J.H. BLANFORD. Model for simulating surface evaporation and biomass production utilizing routine meteorological and remote sensing data. Unpaginated. IN: Proc. 1993 ACSM/ASPRS Annual Convention, New Orleans, LA. 16-18 Feb 1993. WCL# 1768. 5303-13210-002-00D.

54. MAUNEY, J.R., B.A. KIMBALL, P.J. PINTER, JR., R.L. LAMORTE, K.F. LEWIN, J. NAGY, and G.R. HENDREY. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric. and Forest Meteorology. WCL# 1759. (ACCEPTED-21 JUN 1993). 5344-11000-005-00D.

55. MORAN, M.S. 1993. Combining remote sensing and modeling for estimating surface evaporation and biomass production. Unpaginated. IN: Proc. Workshop on Thermal Remote Sensing of the Energy and Water Balance Over Vegetation in Conjunction With Other Sensors. LaLonde, France. 20-24 Sep 1993. WCL# 1769. 5344-13660-001-00D.

56. MORAN, M.S. 1993. Remote sensing of daily transpiration of plant canopies using spectral vegetation index and stress index. Unpaginated. IN: Proc. Workshop on Thermal Remote Sensing of the Energy and Water Balance Over Vegetation in Conjunction With Other Sensors. LaLonde, France, 20-24 Sep 1993. WCL# 1770. 5344-13660-001-00D.

57. MORAN, M.S. 1993. Using satellites and airplanes for farm irrigation management in Arizona. p. 100-107. IN: Proc. Use of Remote Sensing Tech. in Irrig. and Drain., Montpellier, France, 2-5 Nov 1993. WCL# 1734. 5344-13660-001-00D.

58. MORAN, M.S., T.R. CLARKE, Y. INOUE, and A. VIDAL. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sensing Environ. WCL# 1771. (ACCEPTED-DEC 1993). 5344-13660-001-00D.

59. MORAN, M.S., T.R. CLARKE, W.P. KUSTAS, M. WELTZ, and S.A. AMER. Evaluation of hydrologic parameters in semiarid rangeland using remotely sensed spectral data. Water Resources Res. WCL# 1665. (ACCEPTED-MAY 1993). 5344-13660-001-00D.

60. MORAN, M.S., R.D. JACKSON, P.N. SLATER, and P.M. TEILLET. 1993. Simplified procedures for retrieval of land surface reflectance from Landsat TM sensor output. p. 85-89. IN: Proc. Workshop on Atmospheric Correction of Landsat Imagery, sponsored by Defense Landsat Program Office, Torrance, CA. 29 Jun - 02 Jul 1993. WCL# 1772. 5344-13660-001-00D.

61. MORAN, M.S., W.P. KUSTAS, A. VIDAL, D.I. STANNARD, J.H. BLANFORD, and W.D. NICHOLS. Use of ground-based remotely sensed data for surface energy balance evaluation of a semiarid rangeland. Water Resources Res. WCL# 1668. (ACCEPTED-MAY 1993). 5344-13660-001-00D.

62. MORAN, M.S., M.A. WELTZ, A. VIDAL, D.C. GOODRICH, S.A. AMER, D.S. AMMON, K. BATCHILY, J. BLANFORD, T.R. CLARKE, L. EASTMAN, D. FOX, D. GELLMAN, M. HODSHON-YATES, H. HENDY, A.R. HUETE, T. KEEFER, K. KIESEL, L. LANE, A.F. RAHMAN, S. SOROOSHIAN, D. TROUFLEAU, and J. WASHBURN. 1993. Evaluating energy balance of semiarid rangeland from combined optical-microwave remote sensing. p. 82-85. IN: Proc. IEEE Topical Symp. on combined Optical-Microwave Earth & Atmos. Sensing, Albuquerque, NM. 22-25 Mar 1993. WCL# 1712. 5344-13660-001-00D.

63. NAKAYAMA, F.S. 1992. Managing water quality in drip irrigation. p. 47-61. IN: CATI Publication No. 921001. IN: Proc. Subsurface Drip Irrigation: Theory, Practices, and Application, California State University, Fresno, CA. WCL# 1673. 5344-13000-005-00D.

64. NAKAYAMA, F.S., G. HULUKA, B.A. KIMBALL, K. LEWIN, J. NAGY, and G.R. HENDREY. Soil carbon dioxide fluxes in natural and CO_2-enriched systems. Agric. and Forest Meteorology. WCL# 1677. (ACCEPTED-AUG 1993). 5344-11000-005-00D.

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79. THOMPSON, A.E., and D.A. DIERIG. Initial selection and breeding of Lesquerella Fendleri, a new industrial oilseed. Industrial Crops and Products. WCL# 1727. (ACCEPTED-26 JUL 1993). 5344-21410-001-00D.

80. THOMPSON, A.E., and F.S. NAKAYAMA. 1993. Commercializing industrial crops: The industrial component. p. 674, 688, 690 & 691. IN: J. Janick and J.E. Simon. (ed.) New Crops. John Wiley and Sons, Inc. New York, NY. WCL# 1748. 5344-21410-001-00D.

81. VIDAL, A., O. TACONET, M.S. MORAN, A.F. RAHMAN, H. PELGRUM, G.J. RIJCKENBERG, P. CELLIER, K. HUMES, and T.R. CLARKE. 1993. Estimation of surface fluxes over canopies during Mac-Europe 1991 campaign using combined microwave and optical data. p. 90-94. IN: Proc. IEEE Topical Symp. on Combined Optical-Microwave Earth & Atmosphere Sensing, Albuquerque, NM. 22-25 Mar 1993. WCL# 1720. 5344-13660-001-00D.

82. WALTER-SHEA, E.A., C.J. HAYS, M.A. MESARCH, and R.D. JACKSON. 1993. An improved goniometer system for calibrating field reference-reflectance panels. Remote Sensing of Environ. 43:131-138. WCL# 1643. 5344-13660-001-00D.

83. WALL, G.W., J.S. AMTHOR, and B.A. KIMBALL. COTCO2: A cotton growth simulation model for global change. Agric. and Forest Meteorology. WCL# 1760. (ACCEPTED-13 AUG 1993). 5344-11000-005-00D.

84. WALL, G.W., and B.A. KIMBALL. Biological databases derived from free-air carbon dioxide enrichment experiments. IN: E.D. Schulze and H.A. Mooney (ed.) Design and Execution of Experiments on CO_2 Enrichment. Invited book chap. WCL# 1754. (ACCEPTED-01 MAY 1993). 5344-11000-005-00D.

APPENDIX B

Manuscripts Published or Approved as Special Issues or Projects in 1993

Agricultural and Forest Meteorology[1]

Special Issue on FACE

Guest Editors:
William A. Dugas, Texas A&M Agric. Expt. Sta., Blackland Res. Ctr, Temple, TX
Paul J. Pinter, Jr., USDA-ARS, U. S. Water Conservation Laboratory, Phoenix, AZ

Akin, D.E., Kimball, B.A., Mauney, J.R., LaMorte, R.L., Hendrey, G.R., Lewin, K., Nagy, J. and Gates, R.N. Influence of enhanced CO_2 concentration and irrigation on sudangrass digestibility.

Bhattacharya, N.C., Radin, J.W., Kimball, B.A., Mauney, J.R., Hendrey, G.R., Nagy, J., Lewin, K.F. and Ponce, D.C. Diurnal changes in leaf water potential and stomatal conductance in cotton under optimal and limiting water levels in a free-air CO_2 enriched environment.

Dugas, W.A., Heuer, M.L., Hunsaker, D., Kimball, B.A., Lewin, K.F., Nagy, J. and Johnson, M. Sap flow measurements of transpiration from cotton grown under ambient and enriched CO_2 concentrations.

Dugas, W.A. and Pinter, Jr., P.J. Introduction to the Free-Air Carbon dioxide Enrichment (FACE) cotton project.

Hendrey, G.R. and Kimball, B.A. The FACE program.

Hendrix, D.L., Mauney, J.R., Kimball, B.A., Lewin, K., Nagy, J. and Hendrey, G. Influence of elevated CO_2 and mild water stress on nonstructural carbohydrates in field-grown cotton tissues.

Hileman, D.R., Huluka, G., Kenjige, P.K., Sinha, N., Bhattacharya, N.C., Biswas, P.K., Lewin, K.F., Nagy, J., and Hendrey, G.R. Canopy photosynthesis and transpiration of field-grown cotton exposed to free-air CO_2 enrichment (FACE) and differential irrigation.

Huluka, G., Hileman, D.R., Biswas, P.K., Lewin, K.F., Nagy J. and Hendrey, G.R. Effects of elevated CO_2 and water stress on mineral concentration of cotton.

Hunsaker, D.J., Hendrey, G.R., Kimball, B.A., Lewin, K.F., Mauney, J.R. and Nagy, J. Cotton evapotranspiration under field conditions with CO_2 enrichment and variable soil moisture regimes.

[1] Publication of this special issue of *Agricultural and Forest Meteorology* is expected in 1994.

Idso, S.B., Kimball, B.A., Wall, G.W., Garcia, R.L., LaMorte, R., Pinter, Jr., P.J., Mauney, J.R. Hendrey, G.R., Lewin, K. and Nagy, J. Effects of free-air CO_2 enrichment on the light response curve of net photosynthesis in cotton leaves.

Kimball, B.A., LaMorte, R.L., Seay, R.S., Pinter, Jr., P.J., Rokey, R.R., Hunsaker, D.J., Dugas, W.A., Heuer, M.L., Mauney, J.R., Hendrey, G.R., Lewin, K.F. and Nagy, J. Effects of free-air CO_2 enrichment on energy balance and evapotranspiration of cotton.

Leavitt, S.W., Paul, E.A., Kimball, B.A., Hendrey, G.R., Mauney, J.R., Rauschkolb, R., Rogers, H., Lewin, K.F., Nagy, J., Pinter, Jr., P.J. and Johnson, H.B. Carbon isotope dynamics of free-air CO_2 enriched cotton and soils.

Lewin, K.F., Hendrey, G.R., Nagy, J. and LaMorte, R. Design and application of a free-air carbon dioxide enrichment facility.

Mauney, J. R., Kimball, B. A., Pinter, Jr., P.J., LaMorte, R.L., Lewin, K.F., Nagy, J. and Hendrey, G.R. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment.

Nagy, J., Lewin, K.F., Hendrey, G.R., Hassinger, E. and LaMorte, R. Face facility CO_2 concentration control and CO_2 use in 1990 and 1991.

Nakayama, F.S., Huluka, G., Kimball, B.A., Lewin K.F., Nagy, J. and Hendrey, G.R. Soil carbon dioxide fluxes in natural and CO_2-enriched systems.

Pinter, Jr., P.J., Idso, S.B., Hendrix, D.L., Rokey, R.R., Rauschkolb, R.S., Mauney, J.R., Kimball, B.A., Hendrey, G.R., Lewin, K.F. and Nagy, J. Effect of free-air CO_2 enrichment on the chlorophyll content of cotton leaves.

Pinter, Jr., P.J., Kimball, B.A., Mauney J.R., Hendrey, G.R., Lewin, K.F. and Nagy, J. Effects of free-air CO_2 enrichment on PAR absorption and conversion efficiency by cotton.

Prior, S.A., Rogers, H.H., Runion, G.B. and Mauney, J.R. Effects of free-air CO_2 enrichment on cotton root growth.

Runion, G.B., Curl, E.A., Rogers, H.H., Backman, P.A., Rodríguez-Kábana, R. and Helms, B.E. Effects of free-air CO_2 enrichment on microbial populations in the rhizosphere and phyllosphere of cotton.

Wall, G. W., Amthor, J. S. and Kimball, B. A. COTCO2: A cotton growth simulation model for global change.

Wood, C.W., Torbert, H.A., Rogers, H.H., Runion, G.B. and Prior, S.A. Free-air CO_2 enrichment effects on soil carbon and nitrogen.

Remote Sensing of Soils and Vegetation

A workshop to explore applications of remote sensing technology for the evaluation and management of environmental resources and honoring the contributions of Dr. Ray D. Jackson

January 6, 1993; Tempe, AZ

Workshop Organization: Paul J. Pinter, Jr.; and M. Susan Moran
USDA-ARS, U. S. Water Conservation Laboratory, Phoenix, AZ

SESSION I. RESEARCH PRIORITIES AND FUTURE DIRECTIONS - Invited Speakers.
Robert Reginato, Moderator

RESEARCH PRIORITIES FROM A UNIVERSITY PERSPECTIVE
Donald R. Nielsen, Professor, University of California, Davis CA

AGRICULTURAL RESEARCH IN A CHANGING ENVIRONMENT
Jan van Schilfgaarde, Associate Deputy Administrator, Natural Resources and Systems, USDA, Agricultural Research Service, Beltsville, MD

MONITORING EARTH SURFACE PROCESSES AND RESOURCES FROM SPACE
Vincent V. Salomonson, Director of the Earth Sciences Directorate, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD

AGRICULTURAL AND REMOTE SENSING RESEARCH: A EUROPEAN PERSPECTIVE
Alain Perrier, Department of Bioclimatologie, INRA, Grignon 78850 Thiveral, FRANCE

WORKSHOP PERSPECTIVES
Ray D. Jackson, Chief Scientist, USDA, Agricultural Research Service, U.S. Water Conservation Laboratory, Phoenix, AZ

A FARMER'S PERSPECTIVE
Henry A. Brubaker, Farm Manager, Martori Farms, Aguila, AZ

SESSION II. SENSOR SYSTEMS: DESIGN, CALIBRATION AND COMPENSATION FOR VIEW ANGLE AND ATMOSPHERIC EFFECTS - Phil Teillet, Session Chair

A REVIEW OF THE ON-BOARD CALIBRATION METHODOLOGIES FOR FIVE OF THE EARTH OBSERVING SYSTEM SENSORS, Philip N. Slater

SPOT CALIBRATION METHODS AND RESULTS, Magdeleine Dinguirard and Patrice Henry

ESTIMATING GROUND LEVEL REFLECTANCE FROM SPOT-HRV, LANDSAT-TM AND NOAA-AVHRR, Gérard Guyot and Xing-Fa Gu

LOCAL AND REGIONAL EVAPORATION IN ARID ECOSYSTEMS, Lawrence E. Hipps

REGIONAL SCALE EVAPORATION, Marc B. Parlange and Gabriel G. Katul

FIELD-SCALE ESTIMATES OF DAILY EVAPORATION BASED ON HIGH-SPATIAL-RESOLUTION OPTICAL REMOTE SENSING, M. Susan Moran, Thomas R. Clarke and Abdullah F. Rahman

SYNERGISM OF MULTISPECTRAL OBSERVATIONS IN THE CONTEXT OF ESTIMATING REGIONAL EVAPORATION, Bhaskar J. Choudhury

EVALUATING EVAPOTRANSPIRATION FROM SPARSE VEGETATION, J. M. Ham and J. L. Heilman

EFFECTS OF FREE-AIR CO_2 ENRICHMENT ON ENERGY BALANCE AND EVAPOTRANSPIRATION, B. A. Kimball, R. L. LaMorte, R. S. Seay, P. J. Pinter, Jr., R. R. Rokey, D. J. Hunsaker, W. A. Dugas, M. L. Heuer, J. R. Mauney, G. R. Hendrey, K. F. Lewin, and J. Nagy

DIURNAL TRENDS IN WHEAT CANOPY TEMPERATURE, PHOTOSYNTHESIS, AND EVAPOTRANSPIRATION, Donald C. Reicosky, Paul W. Brown, and M. Susan Moran

THE SENSIBLE HEAT FLUX SIGNAL FROM RIPENING WHEAT, Lloyd W. Gay

COMBINED USE OF OPTICAL AND MICROWAVE REMOTE SENSING FOR THE ESTIMATION OF SURFACE ENERGY BALANCE COMPONENTS OVER A SEMI-ARID WATERSHED, K. S. Humes, W. P. Kustas, T. J. Jackson, T. J. Schmugge, M. S. Moran, and W. D. Nichols

ESTIMATES OF EVAPOTRANSPIRATION, CANOPY STRUCTURE, AND BIOMASS IN A CALIFORNIA COASTAL GRASSLAND USING SPECTRAL MIXTURE ANALYSIS ON ADVANCED VISIBLE/INFRARED IMAGING SPECTROMETER (AVIRIS) DATA, Susan L. Ustin, Glen M. Green, John A. Gamon, Christopher B. Field, and Riccardo Valentini

SESSION V. REMOTE SENSING TECHNIQUES AS TOOLS FOR RESOURCE MANAGERS - Steve Rawlins, Session Chair

A CROP CALENDAR FOR SPRING WHEAT, Armand Bauer

REMOTELY SENSED CROP COEFFICIENTS FOR IMPROVED CORN IRRIGATION SCHEDULING, Walter C. Bausch

ESTIMATION OF PLANT WATER STATUS FROM OPTICAL AND THERMAL RADIATION, Blaine L. Blad

IMPLEMENTING A REMOTE SENSING/AGMET MODEL IN A GIS, Steve Maas, G. L. Anderson, and J. D. Hansen

CHANGE DETECTION OF DUST STORMS AND VEGETATION CHANGES IN THE SOUTHWESTERN UNITED STATES, Pat S. Chavez, Jr. and Dave MacKinnon

REMOTE SENSING APPLIED TO FOREST FIRE PREVENTION IN MEDITERRANEAN AREAS, Alain Vidal, Claire Devaux, Florence Pinglo, Helène Durand, and Albert Maillet

MEASUREMENT OF CANOPY COMPONENT REFLECTANCE FOR PARAMETERIZING A GEOMETRIC OPTICAL REFLECTANCE MODEL, Janet Franklin

METHODOLOGICAL APPROACHES OF THE AGRICULTURAL AND HYDROLOGICAL PILOT PROJECTS DEVELOPED IN SPOTAVAL PROGRAMME, Marie-José Lefevre

MICROWAVE SOIL MOISTURE MEASUREMENTS FOR RAINFALL-RUNOFF MODELING, David C. Goodrich, Thomas J. Schmugge, and Thomas J. Jackson

REMOTE SENSING APPLICATIONS TO FARM MANAGEMENT, J. L. Hatfield

RECENT DEVELOPMENTS IN THE TECHNOLOGY FOR SENSING OF SOIL SALINITY, J. D. Rhoades

PHOTOGRAPHIC AND VIDEOGRAPHIC OBSERVATIONS FOR DETERMINING AND MAPPING THE RESPONSE OF COTTON TO SOIL SALINITY, C. L. Wiegand, J. D. Rhoades, D. E. Escobar, and J. H. Everitt

AN INTEGRATED DATA ACQUISITION SYSTEM FOR AERIAL SPECTRORADIOMETRY AND VIDEOGRAPHY, Robert D. Martin, Stephen M. Dewhurst and Marvin E. Bauer

REAL TIME ENVIRONMENTAL AND AGRICULTURAL MONITORING FROM AIRCRAFT AND SPACECRAFT, Randall S. Pearson, John A. Grace and George A. May

Symposium on New Industrial Crop Development[1]

In honor of the work and achievements of Dr. A.E. "Tommy" Thompson

September 27, 1993; New Orleans, LA

Symposium Organization: David A. Dierig
USDA-ARS, U. S. Water Conservation Laboratory, Phoenix, AZ

Introduction to Symposium and ARS's Role in New Crop Development
Henry Shands, Associate Deputy Administrator, USDA-ARS

Historical Perspectives on Potential New Crops, Lesquerella and Guayule as Examples
Reed Rollins, Asa Gray Professor of Systematic Botany, Emeritus, Harvard

Germplasm Collection and Evaluation of New Crops
Calvin Sperling, Plant Exploration Officer, USDA-ARS, NGRL

Diverse Chemical Composition in Seed Germplasm
Robert Kleiman, Research Chemist, USDA-ARS, NCAUR

Recent Developments on New Industrial Crops in The Netherlands
Louis van Soest, Section Leader-Potential Crops, CPRO-DLO, The Netherlands

Developing Breeding Strategies for New Crops
Steven Knapp, Professor, Oregon State University

Establishing Cultural Practices for New Crops
Bobby Phipps, Director - Cotton Research, Agrigenetics Co.

Luncheon, with Keynote Speaker;
Robert J. Reginato, Pacific West Area Director, USDA-ARS

The Role of Universities in New Crop Development
Dennis Ray, Professor, The University of Arizona

Products from New Oilseed Crops
Kenneth Carlson, Research Chemist, USDA-ARS, NCAUR

Marketing Development and Commercialization of New Crops
Keith Walker, Director, Planning and Licensing, Mycogen Corp.

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1 Proceedings forthcoming.

Examining New Crops Market Opportunity
James Brown, President, International Flora Technologies, LTD

Summary of Symposium
A.E. Thompson, Research Geneticist, USDA-ARS, USWCL

23rd Annual Workshop on Crop Simulation

April 5-7, 1993; Tempe, AZ

Workshop Chairperson: Gary W. Wall
USDA-ARS, U. S. Water Conservation Laboratory, Phoenix, AZ

Presiding - Floyd Adamsen, USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona

I. Crop Models and Management

An Application of The Modular Modeling System - MMS. *V.A. Ferreira, USDA-ARS, Great Plains Systems Research, Fort Collins, Colorado; D.G. DeCoursey, USDA-ARS, TERRA Laboratory, Fort Collins, Colorado; and G.H. Leavesley, USGS-WRD, Denver Federal Center, Lakewood, Colorado*

Crop Simulation with Calculated Solar Radiation. R.L. Vanderlip, Agronomy Department, Kansas State University, Manhattan, Kansas

The 92 On-Farm Validation of the Soybean Simulation Model, GLYCIM. *F.D. Whisler, H.F. Hodges, Department of Agronomy, Mississippi State University, Mississippi State, Mississippi; A. Trent, Department of Plant, Soils and Entomological Sciences, University of Idaho, Moscow, Idaho; V.R. Reddy, and B. Acock, USDA-ARS, Systems Research Laboratory, Beltsville, Maryland*

Comparison of a Simple Simulation-based Strategy for Scheduling Water and Nitrogen to Intensive Commercial Potato Production Practices. *T. Hodges, USDA-ARS, Irrigated Agriculture Research, Prosser, Washington*

CropSyst, A Cropping Systems Simulation Model. *C.O. Stockle, R. Nelson, and G.S. Campbell, Department of Biological Systems Engineering, Washington State University, Pullman, Washington*

II. Soil Processes

2DSOIL - A New Two-Dimensional Modular Simulator of Soil and Root Processes for Interfacing with Plant and Micrometeorological Models. *Ya.A. Pachepsky, Agronomy Department, University of Maryland, College Park, Maryland; D. Timlin, B. Acock, and H. Lemmon, USDA-ARS, Beltsville, Maryland; and A. Trent, Department of Plant, Soil, and Entomological Sciences, University of Idaho, Moscow, Idaho*

A Proposed Scheme for Establishing Discharge/Recharge Indices. *Hsin-i (Wally) Wu and J. Walker, Center for Biosystems Modelling, Industrial Engineering Department, Texas A&M University, College Station, Texas*

Simulation of Reference Evapotranspiration in Arid Regions. A. Marani, U.S., U.S. Cotton Research Station, Shafter California; and C.J. Phene, USDA-ARS Water Management Research Laboratory, Fresno, California

Ecological Controls on Microbial Activity in Soils: Theory and Mathematical Modelling. *R.F. Grant, N.G. Juma, and W.B. McGill, Department of Soil Science, University of Alberta, Edmonton, Canada*

Poster Session

A Mechanistic Model for Flue-Cured Tobacco. *S.M. Schneider, USDA-ARS, Crops Research Laboratory, Oxford, North Carolina*

Path Analysis of Tomato Yield, Quality, and Competition with Black and Eastern Black Nightshade (*Solanum nigrum* L. and *S. ptycanthum* Dun.). *M.E. McGiffen, Jr., Department of Botany and Plant Sciences, University of California, Riverside, California; D.J. Pantone, Texas Agricultural Experiment Station, Blackland Research Center, Temple, Texas; and J.B. Masiunas, Department of Horticulture, University of Illinois, Champaign-Urbana, Illinois*

An Improved Model for Simulating Caryopsis Weight in Grain Sorghum. *R.W. Heiniger and R.L. Vanderlip, Agronomy Department, Kansas State University, Manhattan, Kansas*

Modelling Leaf and Spikelet Primordia Initiation in Salt-Stressed Wheat. *C.M. Grieve, S.M. Lesch, E.V. Maas, and L.E. Francois, USDA-ARS, U.S. Salinity Laboratory, Riverside, California*

Validation and Comparison of Three Models of Photosynthesis. *L.B. Pachepsky, Department of Agronomy, University of Maryland, College Park, Maryland; J.D. Haskett and B. Acock, USDA-ARS, Systems Research Laboratory, BARC-W, Beltsville, Maryland*

An Explanatory Economic Model to Simulate Integrated Weed Management Systems for Wild Oats in Irrigated Barley. *C.M. Dunan, Department of Plant Pathology and Weed Science, Colorado State University, Fort Collins, Colorado; F.D. Moore III, Department of Horticulture, Colorado State University, Fort Collins, Colorado; and P. Westra, Department of Plant Pathology and Weed Science, Colorado State University, Fort Collins, Colorado*

Model Selection for Simulating Wheat Growth on the Canadian Prairies. *A. Toure and D. Major, Soil Sciences Section, Research Station, Agriculture Canada, Alberta, Canada*

Iowa Soil and Weather Data Support for Regional Modeling Using GLYCIM. *J.D. Haskett, USDA-ARS, NRI, SRL Systems Research Laboratory, BARC-W, Beltsville, Maryland: Y.A. Pachepsky, Department of Agronomy, University of Maryland, College Park, Maryland; and B. Acock, USDA-ARS, NRI, SRL Systems Research Laboratory, BARC-W, Beltsville, Maryland*

Presiding - Richard Garcia, USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona

III. Modeling Physiological Response

Modeling Temperature Effects on Growth and Photosynthesis of Peanut. *K.J. Boote, N. Pickering, and J.W. Jones, Departments of Agronomy and Agricultural Engineering, University of Florida, Gainesville, Florida*

Rubisco-based Models for Predicting the Response of Leaf Photosynthesis to Rising Temperatures and Atmospheric CO_2 Concentration. *S.P. Long, Department of Applied Science, Brookhaven National Laboratory, Upton, New York; and S. Humpries, Department of Biology, University of Essex, Colchester, United Kingdom*

Empirical Modeling of Plant Gas Fluxes in a Controlled Environment Chamber. *J.D. Cornett, J.E. Hendrix, C.W. Ross, and W.Z. Sadeh, Colorado State University, Fort Collins, Colorado*

If Newton Followed Einstein. The Separate Paths of Modeling, Statistics, and Science. *R.M. Caldwell, University of Hawaii, Department of Agronomy and Soil Science, Honolulu, Hawaii*

GLYCIM: A Mechanistic Soybean Simulation Model. *T. Trent, P. Amonson, Department of Plant, Soil, and Entomological Sciences, University of Idaho, Moscow, Idaho, F.D. Whisler, Department of Agronomy, Mississippi State University, Mississippi State, Mississippi; and V.R. Reddy, USDA-ARS, Systems Research Laboratory, Beltsville, Maryland*

Poster Session

Thermal-Photoperiod Requirement for Soybean Floral Bud Growth. *L.-X. Zhang, R.-F. Wang, Department of Agronomy, University of Illinois, Champaign-Urbana, Illinois; and J.D. Hesketh, USDA-ARS Photosynthesis Research Unit, Champaign-Urbana, Illinois*

Rapid Responses of Soybean Leaf Photosynthesis to Rapid Changes in Atmospheric CO_2 (400-800 ppm) at High Humidities. *X-M. Chen, D-Q. Xu, Department of Agronomy, University of Illinois, Champaign-Urbana, Illinois; and J.D.Hesketh, USDA-ARS Photosynthesis Research Unit, Champaign-Urbana, Illinois*

The Tallgrass Prairie and Wetlands: People Change vs. Climate Change. *H.L. Fu, Jackson State University, Jackson, Mississippi; X.M. Chen, G.B. Begonia, D.M Alm, University of Illinois, Champaign-Urbana, Illinois; and J.D. Hesketh, USDA-ARS Photosynthesis Research Unit, Champaign-Urbana, Illinois*

Modular Structure of COTCO2: A Cotton Simulation Model for Global Change. *G.W. Wall, M.L. Reaves, and B.A. Kimball, USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona*

Software Demonstrations

A Graphical User Interface for Development of Plant Growth Models. *S.M. Schneider, USDA-ARS, Crops Research Laboratory, Oxford, North Carolina*

GLYCIM: A Mechanistic Soybean Simulation Model. *P. Amonson, T. Trent, Department of Plant, Soil, and Entomological Sciences, University of Idaho, Moscow, Idaho; F.D. Whisler, Department of Agronomy, Mississippi State University, Mississippi State, Mississippi; and V.R. Reddy, USDA-ARS, Systems Research Laboratory, Beltsville, Maryland*

SIMPOTATO: A model to Simulate Potato Growth and Yield. *Tom Hodges, USDA-ARS, Irrigated Agriculture Research, Prosser, Washington*

An Application of The Modular Modeling System - MMS. *V.A. Ferreira, USDA-ARS Great Plains Systems Research, Fort Collins, Colorado; D.G. DeCoursey, USDA-ARS TERRA Laboratory, Fort Collins, Colorado; and G.H. Leavesley, USGS-WRD, Denver Federal Center, Lakewood, Colorado*

Rubisco-based Models for Predicting the Response of Leaf Photosynthesis to Rising Temperatures and Atmospheric CO_2 Concentration. *S.P. Long, Department of Applied Science, Brookhaven National Laboratory, Upton, New York; and S. Humpries, Department of Biology, University of Essex, Colchester, United Kingdom*

Presiding - Robert Caldwell, University of Hawaii, Manoa, Hawaii

Simulation of the Winter Wheat Agroecosystem Using the Model DEMETER. *T. Kartschall, Potsdam-Institute for Climate Impact Research, Ecosystems Department, Berlin, Germany*

Investigations of Radiation and Water Transfer Between Soil, Vegetation and Atmosphere Using the Winter Wheat Model DEMETER. *S. Grossman, Postdam-Institute for Climate Impact Research, Ecosystems Department, Berlin, Germany*

Miniworkshop on multi-species modeling: Simulation of weed/crop, tree/crop, and crop/crop systems

Opening: Introductions and overview of multi-species problems.

On-going model development: Summary of existing modeling efforts.

Two-dimensional models: Overview of multi-species systems that are strongly two-dimensional. Soil and canopy models for their simulation.

Technical issues: Software and hardware standards, current and envisioned. Object-oriented programming versus other methods.

End-Users: Who will be using multi-species models and for what purposes?

Knowledge gaps and research priorities

Opportunities for collaboration and research funding: The international Geosphere-Biosphere Program. Potential hypothesis-driven research proposals and avenues for funding

CropSys: a simulation model for multiple cropping systems: Simulation examples. Key distinctive. Current status of field research. Software development plans. Questions about the end of the international Benchmark Sites Network for Agrotechnology transfer (IBSNAT) and interfacing with IBSTAT's Decision Support System for Agrotechnology Transfer (DSSAT).

Water Resources Research[1]

Special Issue dedicated to the Monsoon '90 Experiment

Editor:
S. Sorooshian, Dept. of Hydrology & Water Resources, Univ. of AZ, Tucson
Guest Editors:
W.P. Kustas, USDA-ARS, Hydrology Laboratory, Beltsville, MD
D. C. Goodrich, USDA-ARS, Southwest Watershed Research Center, Tucson, AZ

Chehbouni, A., Y.H. Kerr, J. Qi, A.R. Huete, S. Sorooshian (1994) Towards the development of multidirectional vegetation index, Water Resources Research (Accepted October 1993).

Goodrich, D.C., T.J. Schmugge, T.J. Jackson, C.L. Unkrich, T.O. Keefer, R. Parry, L.B. Bach, and S.A. Amer (1994) Runoff simulation sensitivity measurements to remotely sensed initial soil water content, Water Resources Research (Accepted October 1993).

Hipps, L.E., E. Swiatek and W.P. Kustas (1994) Interactions between regional surface fluxes and the ABL over a heterogeneous watershed, Water Resources Research (Accepted October 1993).

Humes, K.S., W.P. Kustas, M.S. Moran, W.D. Nichols and M.A. Weltz (1994a) Variability in emissivity and surface temperature over a sparsely vegetated surface, Water Resources Research Accepted October 1993).

Humes, K.S., W.P. Kustas and M.S. Moran (1994b) Use of remote sensing and reference site measurements to estimate instantaneous surface energy balance components over a semi-arid rangeland watershed, Water Resources Research (Accepted october 1993).

Kustas, W.P. and D.C. Goodrich (1994) Preface to the Special Section on Monsoon '90, Water Resources Research (Accepted October 1993).

Kustas, W.P., J.H. Blanford, D.I. Stannard, C.S.T. Daughtry, W.D. Nichols and M.A. Weltz (1994a) Local energy flux estimates for unstable conditions using variance data in semi-arid rangelands, Water Resources Research (Accepted October 1993).

Kustas, W.P., M.S. Moran, K.S. Humes, D.I. Stannard, P.J. Pinter, Jr., L.E. Hipps, E. Swiatek and D.C. Goodrich (1994b) Surface energy balance estimates at local and regional scales using optical remote sensing from an aircraft platform and atmospheric data collected over semiarid rangelands, Water Resources Research (Accepted October 1993).

[1] Publication of this special issue of *Water Resources Research* is expected in 1994.

Menenti, M. and J.C. Ritchie (1994) Estimation of effective aerodynamic roughness of Walnut Gulch watershed with laster altimeter measurements, Water Resources Research (Accepted October 1993).

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